NASA Technical Memorandum 4093

A Comparison of Two Trusses for the Space Station Structure

(NASA-TM-4093) A COMPARISON OF TWO TRUSSES FOR THE SPACE STATION STRUCTURE (NASA) 23 p
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MARCH 1989

NASA

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A Comparison of Two Trusses for the Space Station Structure

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National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

1989

SUMMARY

The structural performances of two truss configurations, the orthogonal tetrahedral and a Warren-type, are compared using finite element models representing the phase 1 space station. The truss torsional stiffness properties and fundamental torsion frequency are determined using cantilever truss-beam models. Frequencies, mode shapes, transient response, and truss-strut compressive loads are compared for the two space station models. The performance benefit resulting from using a high-modulus truss strut is also presented. Finally, assembly and logistics characteristics of the two truss configurations are evaluated.

INTRODUCTION

The space station truss structure is important because it defines the stiffness characteristics of the space station. The truss structure, which will be transported to a low Earth orbit by a series of shuttle flights, will be erected in space by astronauts. The truss grows from 180 ft in length, after the first shuttle flight, to 510 ft when the station reaches its final configuration, known as the phase 1 space station. The truss configurations evaluated in this paper are an orthogonal tetrahedral truss and a Warren-type truss. The truss configuration is important because the configuration determines the following: how the truss will be assembled in space, the potential for growth, the limits on unanticipated structural modifications, the truss stability with missing struts, the access to interior volume, and the design of the utility distribution system.

The space station truss configuration has received considerable attention during the past several years. In reference 1, the structural performances of a Warren-type truss and an orthogonal tetrahedral truss are evaluated for beam and platform applications including scenarios where individual struts are removed. In reference 2, design requirements are presented for a space station truss structure, and truss-selection criteria (such as stiffness, mass, customer accommodations, operations, and space station construction) are discussed. The requirements and the selection criteria for a space station strut design are presented in reference 3. Recently, five different truss configurations were evaluated in reference 4, and a Warren-type truss configuration was chosen as the most suitable for the space station using criteria such as static performance, assembly time, and ease of operational access.

The first objective of this paper is to assess the dynamic behavior of a space station model using the two truss configurations and to compare the frequencies, transient response characteristics, and strut loads. The second objective is to compare the truss configurations in terms of assembly and logistics considerations. The third and final objective is to determine the effects of strut stiffness on the space station structural performance.

TRUSS DESCRIPTIONS

The truss configurations evaluated in this paper are an orthogonal tetrahedral (OTT) truss shown in figure 1(a) and a Warren-type truss shown in figure 1(b). The configurations have the same number of joints, battens, longerons, and diagonals, and they differ only in the arrangement of the diagonal struts. The longerons and battens are 196.85 in. (5.00 m) long, and the diagonals are 278.4 in. (7.07 m) long. The OTT truss, in a beam application, has either seven or six struts connected to a joint, whereas the Warren-type truss has eight and five. The mass of the truss configurations is identical and the bending stiffness properties are approximately equal since the longerons contribute significantly more than any other struts to the truss bending stiffness. The torsional stiffness properties are not the same, however, because the diagonal struts are arranged differently. In particular, the bending and torsional stiffness properties of the OTT truss are coupled because of the diagonal strut arrangement. This bending-torsion stiffness coupling is not present in the Warren-type truss.

FINITE ELEMENT MODELS

The finite element analysis program used for the analyses is MSC/NASTRAN. (See ref. 5.) In all the analysis models, each truss strut is represented with a single beam-type finite element. This provided sufficient modeling detail to accurately obtain global response quantities. The material and section properties, the buckling loads, and the effective strut modulus (taking into account the stiffness reduction due to the joints) are listed in table I. An 11-bay cantilever truss-beam model was developed for the two truss configurations, one of which is shown in figure 2. Each of the cantilever truss-beam models has 48 nodes and 148 beam elements.

The phase 1 space station model is described in reference 6 and is modified for the current study by using the section and material properties from table I. The finite element models for the phase 1 space station are shown in figures 3 and 4. Since each of the phase 1 models had the identical total mass, any differences in the structural performance would result from the different diagonal arrangement used in each model. The prime docking port, the reaction control system (RCS) thrusters, the module cluster, and the starboard transverse boom tip, which are referred to in the analysis results, are indicated in figures 3 and 4.

ANALYSIS RESULTS

A static analysis, performed with the cantilever truss-beam models, is used to obtain the torsional stiffness of the truss configurations. The fundamental torsion mode, as a function of the strut modulus of elasticity, is also calculated using the cantilever models. The phase 1 space station models are used to calculate frequencies, strut loads, and displacement time histories using two forcing functions. A modal damping factor of 0.5 percent is used in the frequency and transient-response calculations.

Torsional Stiffness

The torsional stiffness of the two truss configurations is calculated using corresponding cantilever truss-beam models. A torque is applied about the Y-axis at the free end of the cantilever truss beam (see fig. 2), and the amount of Y-axis rotation is used to determine a corresponding value of beam torsional stiffness (GJ). The torsional stiffness of the cantilever truss beam is plotted as a function of the truss-strut modulus of elasticity in figure 5. The OTT truss torsional stiffness is 34 percent less than the Warren-type truss stiffness, which agrees with the results presented in reference 4.

Normal Modes

Cantilever Truss-Beam Models

The first torsion frequency, normalized to the Warren-type truss frequency for a strut modulus of 40×10^6 psi, is plotted as a function of the strut modulus of elasticity in figure 6. The fundamental torsion frequency of the OTT truss is approximately 18 percent less than the Warren-type truss frequency for all moduli considered, which would be consistent with the frequencies calculated using the static torsional stiffness previously stated.

Phase 1 Space Station

The undamped modes below a frequency (f) of 2.0 Hz are calculated for the phase 1 space station models. There are 105 modes below 2.0 Hz for the two models; 6 are rigid-body modes, 13 are truss-structure modes, and the remaining 86 are space station appendage modes that are associated with the photovoltaic arrays, station radiators, and photovoltaic radiators. The truss-structure frequencies for each model are plotted as a function of the mode number in figure 7. The fundamental truss-structure mode shape, the second truss-structure mode shape, a higher coupled bending-torsion mode shape, and a complex truss-structure bending-mode shape are shown in figures 8, 9, 10 and 11, respectively.

The mode shapes for each model are normalized to a modal mass of unity as described in reference 7. A mode-shape comparison constant is computed using the normalized mode shapes from the two space station models. The mode-shape comparison constants are listed in table II for the truss-structure modes with the corresponding percent of difference in frequency. The greatest difference in frequency is 14.6 percent and occurs for the fifth and sixth structure modes of the OTT and Warren-type configurations, respectively. The fifth and sixth modes are primarily transverse boom torsion about the Y-axis coupled with some transverse boom bending. The remaining frequencies differ by less than 5 percent.

A summary of the analysis results is shown in table III. As the truss-configuration evaluation method changes from the conservative static analysis to a more representative free-free dynamic analysis, the performance differences between the truss configurations become less significant.

Dynamic Response

Frequency Response

The frequency response for the x-displacement amplitudes at the starboard transverse boom tip is calculated for the space station models using two different excitations. The first excitation is defined as a harmonic forcing function of 1.0-lbf magnitude applied at the prime docking port in the x-direction. The second excitation is defined as a harmonic forcing function of 0.50-lbf magnitude applied simultaneously at each of the two RCS thruster locations in the x-direction. The first excitation is used to obtain the transverse boom tip x-displacement amplitudes shown in figures 12(a) and 12(b) for the OTT and Warren-type configurations, respectively. The predominant mode excited by the first excitation is the second truss-structure mode ($f = 0.25$ Hz) shown in figure 9. The second excitation results in the x-displacement amplitude, shown in figures 13(a) and 13(b), for the OTT truss and the Warren-type truss configurations, respectively. The second truss-structure mode is the predominant mode excited by the RCS thruster firing.

Transient Response

The two forcing functions used to excite the space station models are shown in figure 14. The first function, shown in figure 14(a), has been described as a "failed shuttle docking maneuver" where the shuttle contacts the space station but fails to attach to the station. Hence, the total system mass does not change. This forcing function applies a 500-lbf load at the prime docking port for a duration of 1 sec. The second forcing function, shown in figure 14(b), applies a 50-lbf load simultaneously at each of the two thruster locations for a total impulse to the station of 100 lbf-sec.

Transverse boom displacement. The space station models are subjected to the forcing functions shown in figure 14, and the maximum x-displacement at the starboard transverse boom tip is calculated and shown in figure 15. The maximum x-displacement occurs at approximately 8.5 sec for the docking excitation and at 2.5 sec for the reboost excitation. There is no appreciable difference in tip displacements because of the similarity in the second structure mode, which is excited at 0.25 Hz as shown by the frequency responses in figures 12 and 13.

Truss-strut compressive loads. Truss-strut compressive loads are calculated for the space station models subject to the docking load shown in figure 14(a). The longeron and diagonal truss struts selected are shown in figure 16 for the OTT truss. The corresponding struts in the Warren-type truss are also selected. These struts are selected because their loads represent the highest strut loads in the transverse boom. The compressive strut loads are shown in figure 17 for the OTT truss and the Warren-type truss together with the Euler buckling loads given in table I. The maximum longeron compressive load, which occurs in longeron L2 for each truss configuration, is 379 lbf and 367 lbf for the OTT truss and the Warren-type truss, respectively. These compressive loads are at 17.7 percent and 17.2 percent of the buckling load for the OTT and the Warren-type configurations, respectively. Maximum compressive loads occurring in the selected diagonal struts are 115 lbf (D1) and 114 lbf (D2) for the OTT truss and 100 lbf (D1) and 107 lbf (D2) for the Warren-type truss. The diagonal truss struts with the largest compressive loads reach 10.8 percent and 10.0 percent of the diagonal-strut buckling load for the OTT and the Warren-type configurations, respectively.

"Failed strut" analysis. A "failed strut" scenario is defined as a complete and undetected failure of one strut in the space station truss. The effect of a "failed strut" on the dynamic behavior of the space station models is assessed by removing the longeron with the highest compressive load (longeron L2). When the undamped modes are calculated, there are still 105 vibration modes below 2.0 Hz. The frequencies of the truss-structure modes, when longeron L2 is removed, are shown as a function of the mode number in figure 18.

The space station models with the missing longeron are subjected to the failed docking load, and the resulting compressive strut loads are then examined. The maximum compressive loads for the struts highlighted in figure 16 are shown in figure 19. The longeron and diagonal compressive loads are well below their respective Euler buckling loads in each truss configuration. The largest compressive load occurring in the OTT truss longerons (L5) is 409 lbf, or less than 20 percent of the longeron buckling load. The largest compressive load occurring in the Warren-type truss longerons (L3) is 338 lbf, or less than 16 percent of the buckling load. The largest difference in the corresponding strut loads, 115 lbf, occurs in longeron L5. This difference represents less than 6 percent of the longeron buckling load. The maximum compressive load in the diagonal strut D1 is 251 lbf for the OTT truss configuration, which is less than 24 percent of the diagonal buckling load. The corresponding diagonal-strut load in the Warren-type truss is 207 lbf, which is less than 20 percent of the buckling load for diagonal struts.

A study was conducted to determine if higher compressive strut loads could be obtained when longerons other than L2 were removed from the truss. Longerons L8, L3, and L4 were removed one at a time, and the resulting strut compressive loads were then calculated for the failed docking load. Larger strut compressive loads were obtained if longeron L4, rather than longeron L2, was removed from the models. In figure 20, the resulting strut compressive loads are shown for the struts highlighted in figure 16. The maximum compressive load in the OTT truss and the Warren-type truss longerons was 456 lbf and 429 lbf, respectively, occurring in strut L2 for each model. The difference between 456 lbf and 429 lbf is less than 2 percent of the longeron buckling load.

Strut Stiffness

The effect of strut stiffness on the response of the OTT space station model is assessed by exciting the model with the forcing function in figure 14(a) and calculating the response for three values of strut modulus. The x-displacement response is obtained at the starboard transverse boom tip, and the time required for the response to decay to 50 percent of the peak amplitude is determined. The strut modulus values used are 10×10^6 psi, 20×10^6 psi, and 34×10^6 psi and represent the range of moduli currently being considered for the space station struts. The modal damping factor, 0.5 percent for each mode, is the same for each of the three moduli. As the strut modulus increases, the time to decay to 50 percent of the peak amplitude decreases as shown in figure 21. The tip response decayed to 50 percent of the peak amplitude after 135 sec using a strut modulus of 10×10^6 psi, whereas only 40 sec are required with a strut modulus of 34×10^6 psi. For equivalent modal damping, increasing the strut modulus is advantageous because the model vibrates at a higher frequency, thus resulting in shorter decay times.

SPACE STATION ASSEMBLY CONSIDERATIONS

The space station truss structure must provide adequate structural stiffness so that the potential for control-structure interaction problems is minimized. The truss must also allow for evolutionary growth and easily accommodate modifications to the space station configuration over a long period of time. In this section, the assembly and logistics characteristics are discussed for the two truss configurations, and a utility-tray attachment scheme is presented.

Truss Assembly

Assembly concerns for the OTT and Warren-type truss configurations shown in figure 1 have been investigated. Proposed assembly scenarios for both truss configurations use two astronauts—one on each side of the truss beam—working cooperatively in extravehicular activity (EVA) to assemble nodes and struts manually into the required truss configuration. (See refs. 8 and 9.) In general, proposed assembly procedures for both configurations require that nodes and struts be retrieved from stowage canisters by each astronaut. The astronaut is then transported to the desired truss location (by an appropriate device) where the nodes and struts are assembled individually to form the desired truss configuration.

Nodes for the OTT and Warren-type truss configurations must be stowed differently because of their different diagonal-strut patterns. The node structural configuration for these truss types is summarized in table IV. When a beam application is considered, the alternating face and interior diagonal arrangement of the Warren-type truss shown in figure 1 results in the alternating, two-node configuration noted in table IV. From an assembly viewpoint, the Warren-type truss requires an alternating assembly sequence from one bay to the next on each side of the truss beam. Thus, each astronaut is required to change assembly procedures as well as the sequence of node and strut retrieval from their stowage canisters from bay to bay. This requires nodes to be stored in and retrieved from the transportation canister in a specific sequence.

The OTT truss nodes, however, are identical along a beam longeron. (See table IV.) Consequently, each bay added to an OTT truss beam is identical to the adjacent bay, thus simplifying the assembly process. This feature also simplifies node stowage and retrieval and was incorporated in the stowage canister arrangement used for the assembly tests described in reference 8 and shown in figure 22. All upper and lower nodes, relative to the astronaut, were stowed in upper and lower bins in the canister on each side of the beam. For the OTT truss assembly, each astronaut merely repeats one identical procedure for each added bay, thus removing upper nodes from upper bins and lower nodes from lower bins. One direct benefit of the highly repetitive OTT truss-assembly procedure is the unit assembly time of 28 sec per strut (or 6 min per bay) reported in reference 8, which also included utility-tray attachment. The wide discrepancy between this test result (6 min per bay) and the OTT assembly tests reported in reference 4 (14 min per bay) suggests that the methods used in the tests of reference 4 be reexamined.

Astronauts constructing the space station will have many other tasks to perform simultaneously while assembling the truss, such as utility installation and payload attachment. Every effort possible must be made to simplify this myriad of assembly functions to ensure that the level of activity required from the astronauts is reasonable. For many of the space station systems, simplifications may not be possible without operational compromise. Using the OTT truss structure for the space station provides an opportunity to increase astronaut EVA construction productivity without sacrificing structural or dynamic behavior.

Utility-Tray Attachment

Because of the alternating internal diagonal arrangement of the Warren-type truss, illustrated in figure 1(b), interior utility trays must be attached to the center of the batten frame struts or diagonals of the truss. Primary attachment to a truss at any location other than at nodal hardpoints is not considered good structural practice, with one major concern being the reduction of strut axial stiffness due to curvature induced by lateral disturbance. The parallel diagonal arrangement of the OTT truss configuration, however, permits nodal attachment of the utility trays as shown in figure 22 using quick-attachment strut connectors. The attachment location and attachment method of the OTT truss have the following advantages: a structural connection commonality with the truss, no requirement for connectors to be bonded or attached to the center of the struts, and no degradation of strut packaging in, or retrieval from, the strut and node stowage canisters.

Preliminary analysis indicates that sufficient rotational stiffness exists at an OTT truss node so that the fundamental frequency of a 1000-lbm mass cantilevered 2 ft from a node is approximately 2 Hz. Thus, utility trays, which have a mass per truss bay of approximately 1000 lbm, can be supported at a single location in each bay without influencing the major lower structural frequencies. (See fig. 7.)

Truss neutral-buoyancy assembly tests that incorporate 1-bay-long, folded utility-tray mock-ups are reported in reference 8. The utility trays used in the tests were connected to the node as shown in figure 23, and the installation had only a minor impact on truss-assembly times and procedural complexity. The utility trays are attached, as shown in figure 23, at the OTT truss node with six strut connections. (See table IV.) By using a batten-plane connection site, utility-tray installation does not interfere with access to payload connections located either inside or outside the truss. This connection location preserves the uncrowded OTT node condition cited in reference 1 as being preferable over the Warren-type node condition. Even with the utility-tray attachment, the OTT truss-beam nodes remain identical along each longeron.

Crew Translational Aid

Utility trays may also be used to provide a crew translational aid, as shown schematically in figure 23. With this concept, handholds (or a handrail) and a tether slide wire are attached along the interior face of the utility trays in a manner similar to the system attached to the sill of the shuttle cargo bay. The large open area adjacent to the utility trays provides for a secure and unobstructed EVA translation corridor along the truss interior. The open area of the OTT truss available for translation is twice that of the Warren-type truss, which further enhances safety considerations. This translational aid, in addition to having a minimal impact on space station mass, could be significantly less massive than other proposed translational aid designs.

CONCLUDING REMARKS

The static and dynamic behavior of an orthogonal tetrahedral (OTT) truss and a Warren-type truss was compared using finite element models that differed only in diagonal arrangement. Cantilever truss-beam models were used to compare the torsional stiffness properties of the two truss configurations, and two detailed finite element models representing the phase 1 space station were used to evaluate the free-free dynamic behavior. The frequency response was calculated for both truss configurations when subjected to docking and reboost loads. A forcing function representing a "failed shuttle docking maneuver" was applied to determine strut compressive loads for both space station models in two cases: in the first case, the truss-strut compressive loads were compared assuming no truss-strut failures; in the second case, the most highly loaded truss strut from the first case was removed and new compressive strut loads resulting from an applied shuttle docking load were compared.

The dynamic characteristics of the two space station models are not a primary discriminator for selecting a truss configuration because their transient response performance is very similar. Other criteria such as ease of assembly and growth capability are considered to be more significant. Considering these criteria and the truss-assembly tests conducted to date, the OTT truss appears to offer advantages over other trusses for space station structure applications. It has also been shown that modeling portions of the truss structure and using static analysis to predict dynamic behavior are insufficient to accurately assess the performance characteristics of a complex free-flying spacecraft.

The strut modulus chosen for the truss has a large impact on the structural performance of the space station. The truss stiffness, frequency, and strut buckling load all increase with increasing strut modulus. Maximizing the truss-strut modulus will enhance the space station structural performance while also providing increased capability for future space station growth or the addition of new functional requirements.

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January 20, 1989

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Table I. Truss-Member Properties

Strut cross-sectional properties:	
Area, in^2	0.46596
Area moments of inertia I_{XX} and I_{YY}, in^4	0.2475
Polar moment of inertia I_p, in^4	0.4949
Strut material properties:	
Longerons and battens:	
Effective modulus of elasticity,[a] psi	31.26×10^6
Poisson's ratio	0.3
Material density, lbm/in^3	0.068
Diagonals:	
Effective modulus of elasticity,[a] psi	31.96×10^6
Poisson's ratio	0.3
Material density, lbm/in^3	0.068
Euler buckling load:	
Modulus of elasticity, psi	33.8×10^6
Longerons and battens, lbf	2131
Diagonals, lbf	1065

[a]Includes joint stiffness reduction (where joint axial stiffness (EA) is approximately equal to 7.75×10^6 lbf at a 15.5-in. length).

Table II. Comparison of Mode Shapes of Phase 1 Space Station Truss Structure

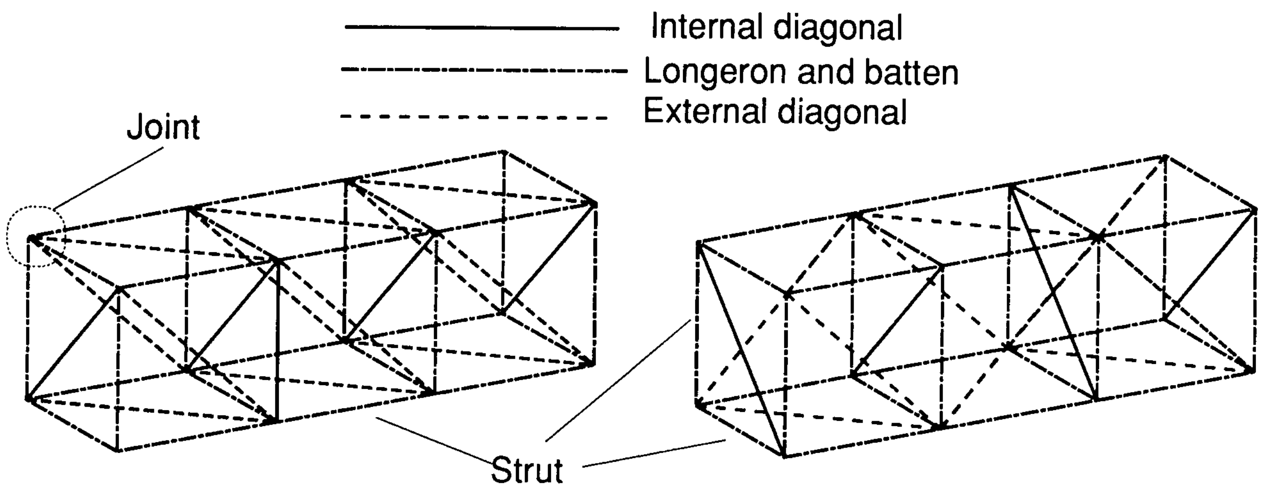
Structure mode		Mode-shape comparison constant	Difference in frequency, percent
OTT	Warren-type		
1	1	0.96	0
2	2	.96	.6
3	3	.88	.2
4	4	.84	0
5	6	.30	14.6
6	5	.63	1.4
7	7	.88	.2
8	8	.85	.8
9	9	.72	1.8
10	10	.70	4.4
11	11	.65	1.9
12	12	.66	.9
13	13	.80	1.4

Table III. Comparison of Analytical Results by Assessment Criterion

Assessment criterion	Difference between OTT and Warren-type trusses
Static analysis of cantilever truss beam (torsional stiffness)	34 percent
Dynamic analysis of cantilever truss beam (first torsion frequency)	18 percent
Dynamic analysis of free-free model of space station (frequencies below 2.0 Hz)	<2.0 percent for modes 1–4, 7–9, 11–13; <5.0 percent for mode 10; <15.0 percent for modes 5–6

Table IV. Node Structural Characteristics

Truss application	Warren-type truss	OTT truss
Beam	• Two nodes per side • Eight and five connections per node • Upper nodes alternate along each side • Lower nodes alternate along each side • Each added bay alternates construction in all three directions	• Two nodes per side • Six and seven connections per node • All upper nodes per side identical • All lower nodes per side identical • Each added bay identical in all three directions
Planar	• Two-node configuration • Seven and eleven connections per node • Nodes alternate in all three directions	• One-node configuration • Nine connections per node • All nodes identical



(a) OTT truss.

(b) Warren-type truss.

Figure 1. Truss configurations evaluated.

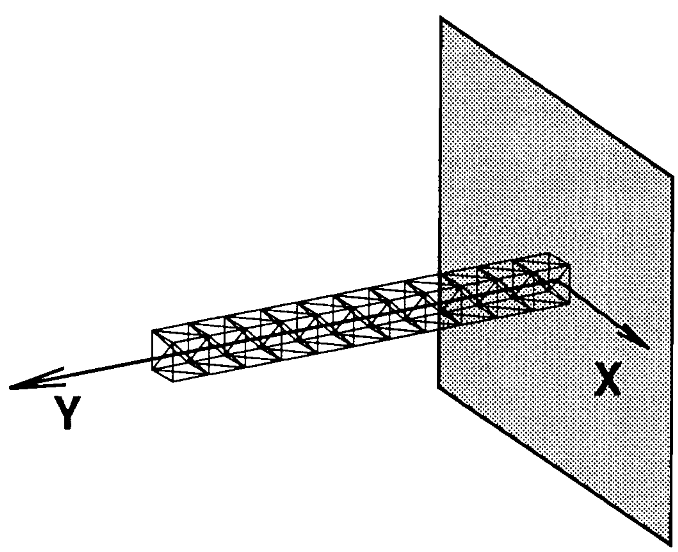


Figure 2. Cantilever truss-beam model.

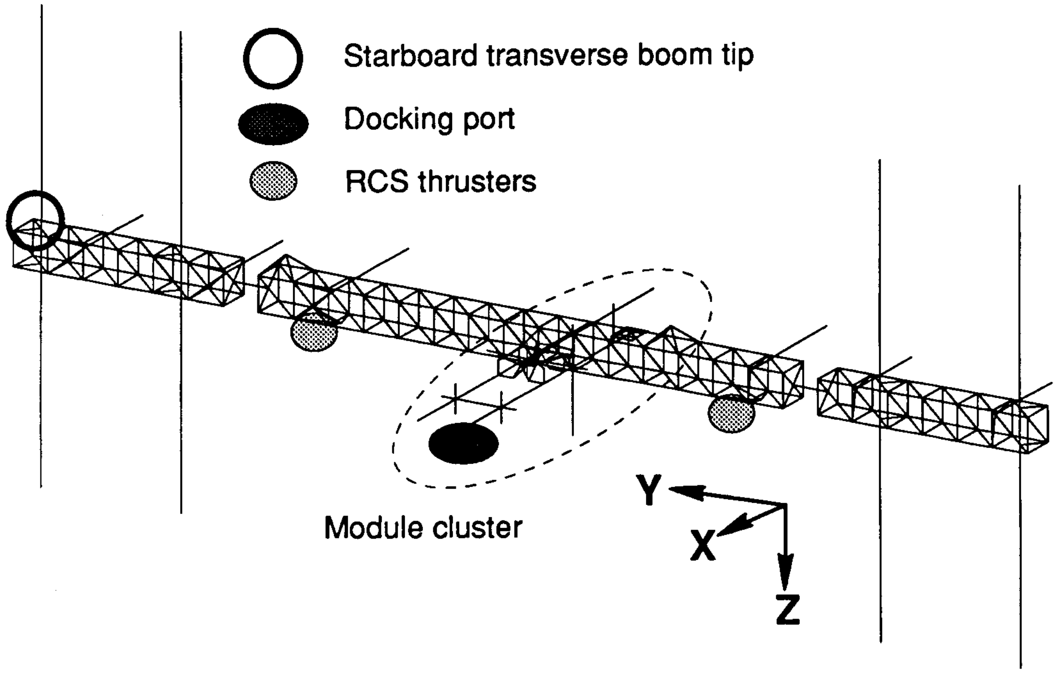


Figure 3. Phase 1 space station model with OTT truss.

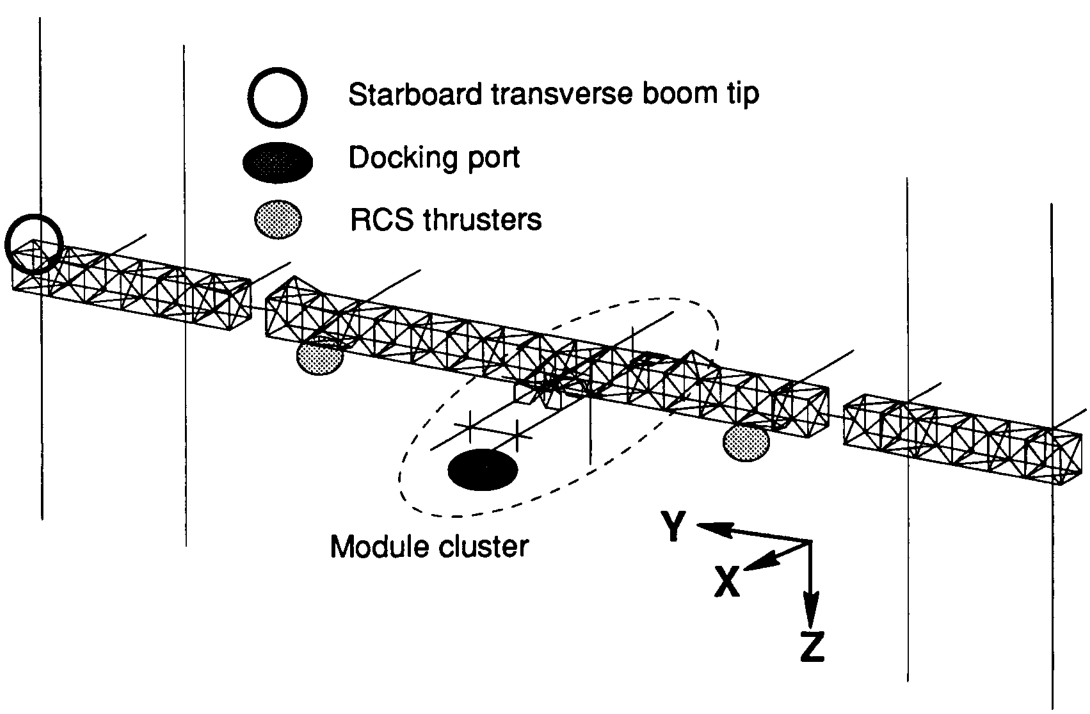


Figure 4. Phase 1 space station model with Warren-type truss.

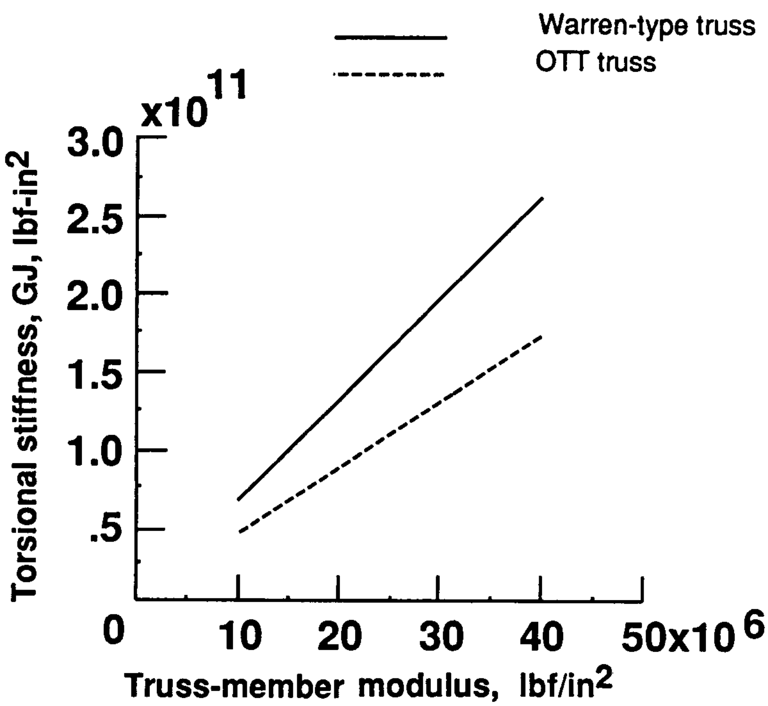


Figure 5. Torsional stiffness of truss configurations.

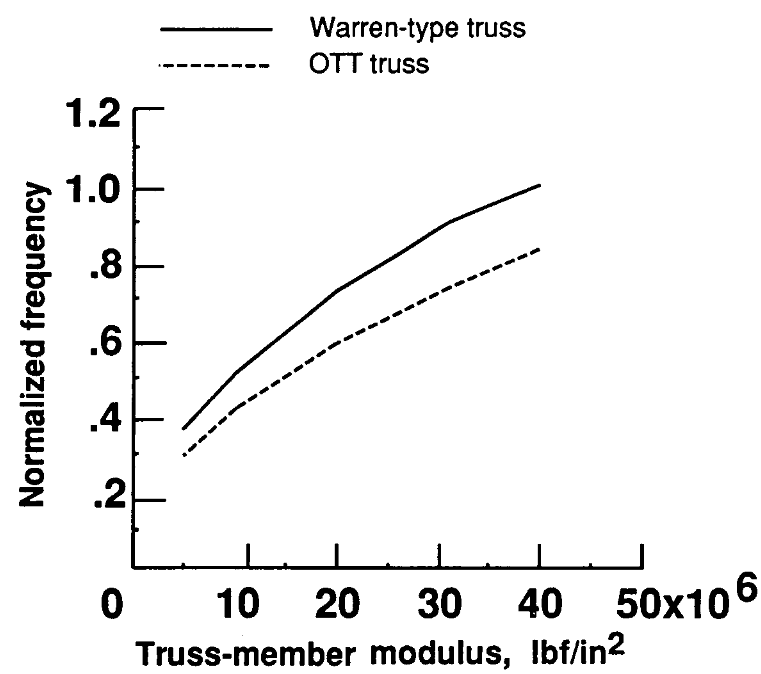


Figure 6. First torsion mode of cantilever truss-beam models.

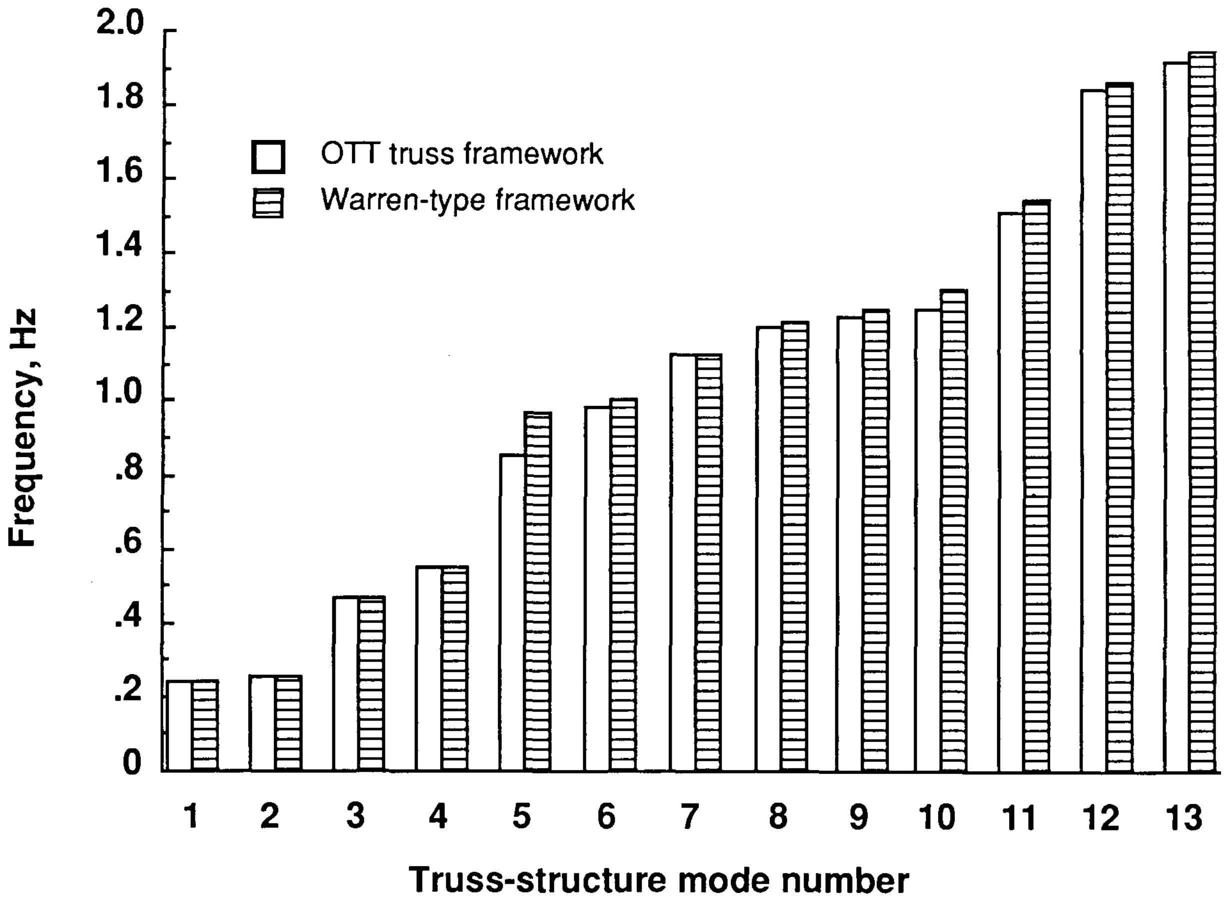


Figure 7. Truss-structure frequencies of space station models.

(a) OTT truss. $f = 0.242$ Hz.

(b) Warren-type truss. $f = 0.243$ Hz.

Figure 8. Fundamental truss-structure mode shape.

(a) OTT truss. $f = 0.253$ Hz.

(b) Warren-type truss. $f = 0.252$ Hz.

Figure 9. Second truss-structure mode shape.

(a) OTT truss. $f = 0.855$ Hz.

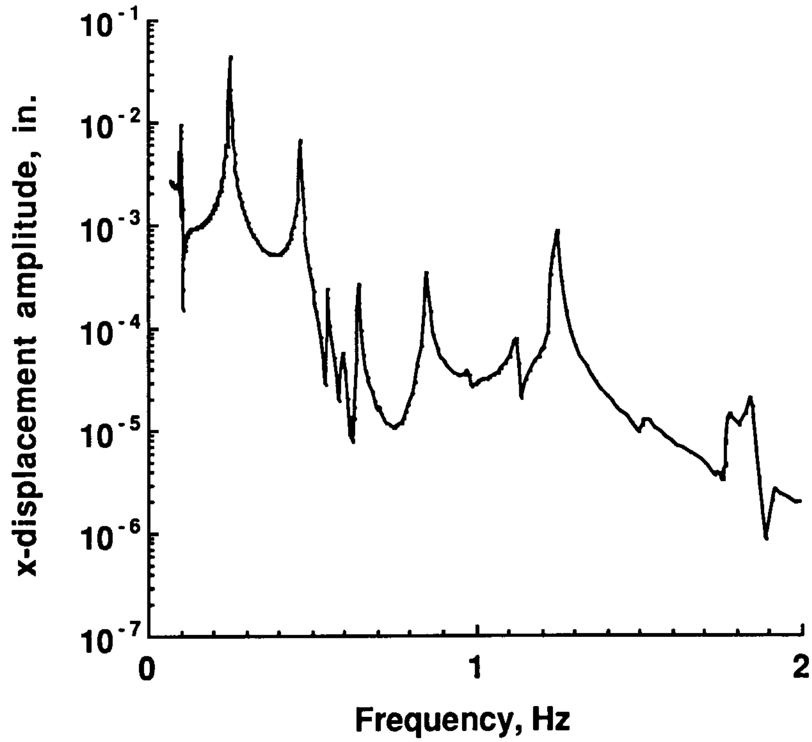
(b) Warren-type truss. $f = 0.969$ Hz.

Figure 10. Fifth truss-structure mode shape.

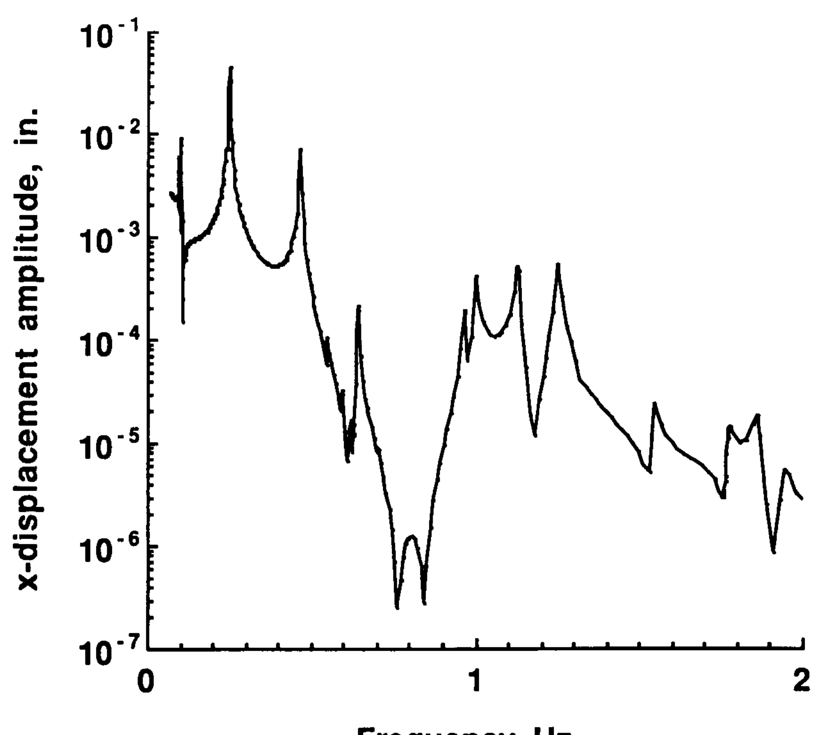
(a) OTT truss. $f = 1.205$ Hz.

(b) Warren-type truss. $f = 1.215$ Hz.

Figure 11. A complex truss-structure mode shape (mode 8).

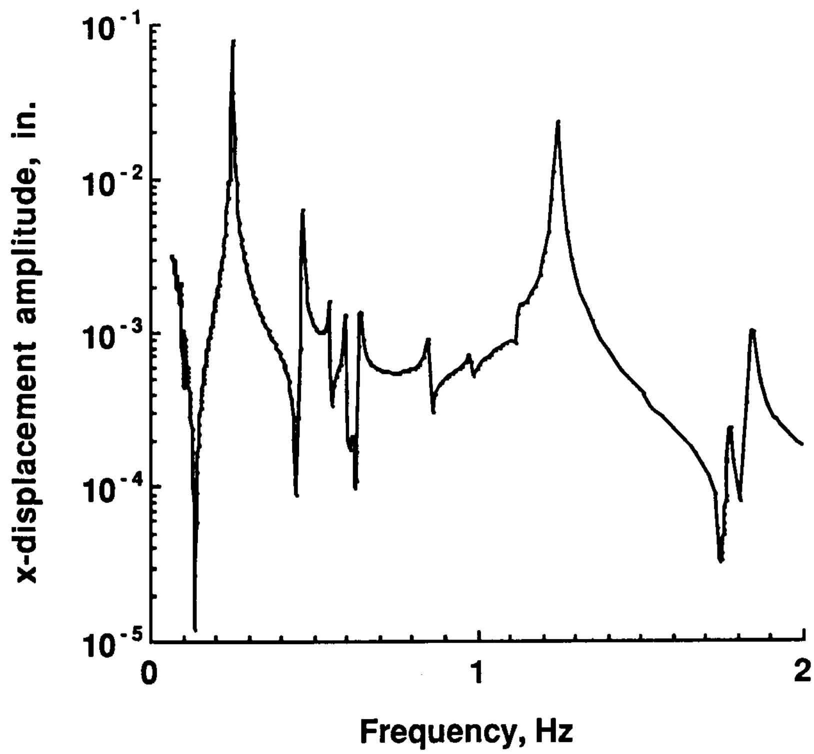


(a) OTT truss.

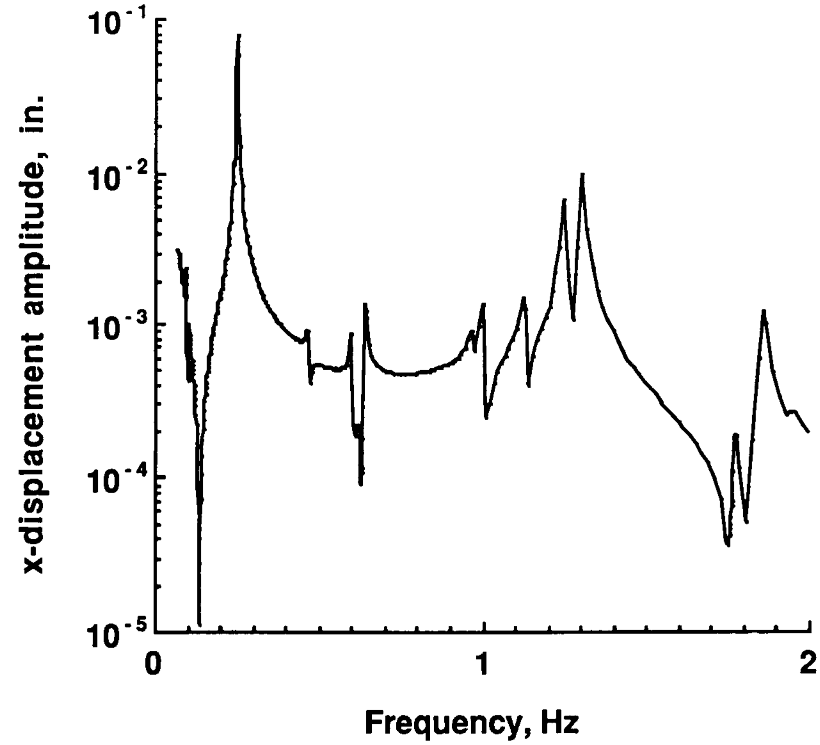


(b) Warren-type truss.

Figure 12. Frequency response at transverse boom tip for shuttle docking excitation.

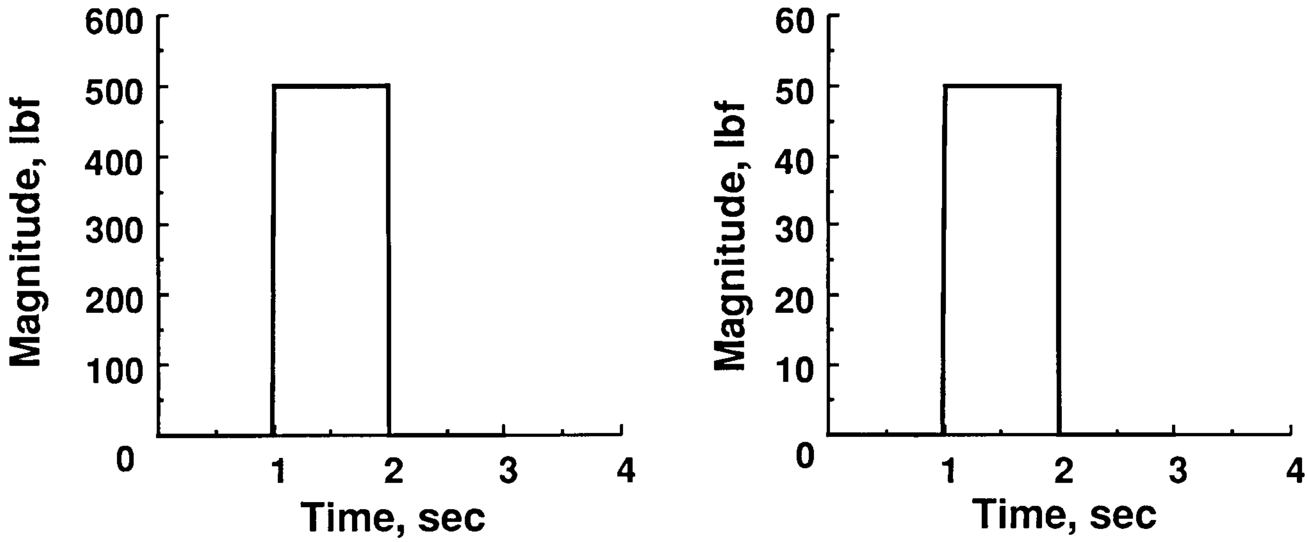


(a) OTT truss.



(b) Warren-type truss.

Figure 13. Frequency response at transverse boom tip for RCS thruster excitation.



(a) Failed shuttle docking.

(b) RCS thruster firing.

Figure 14. Space station applied loads.

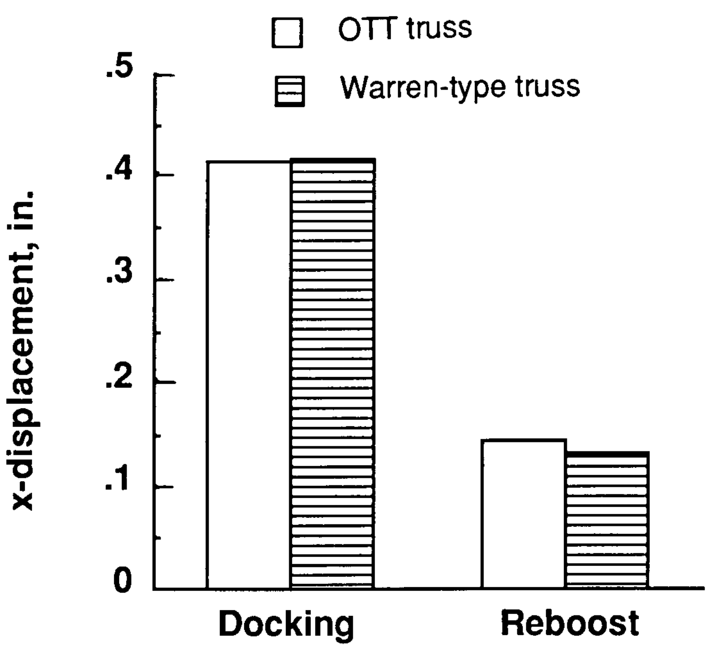


Figure 15. Maximum x-displacement at starboard transverse boom tip.

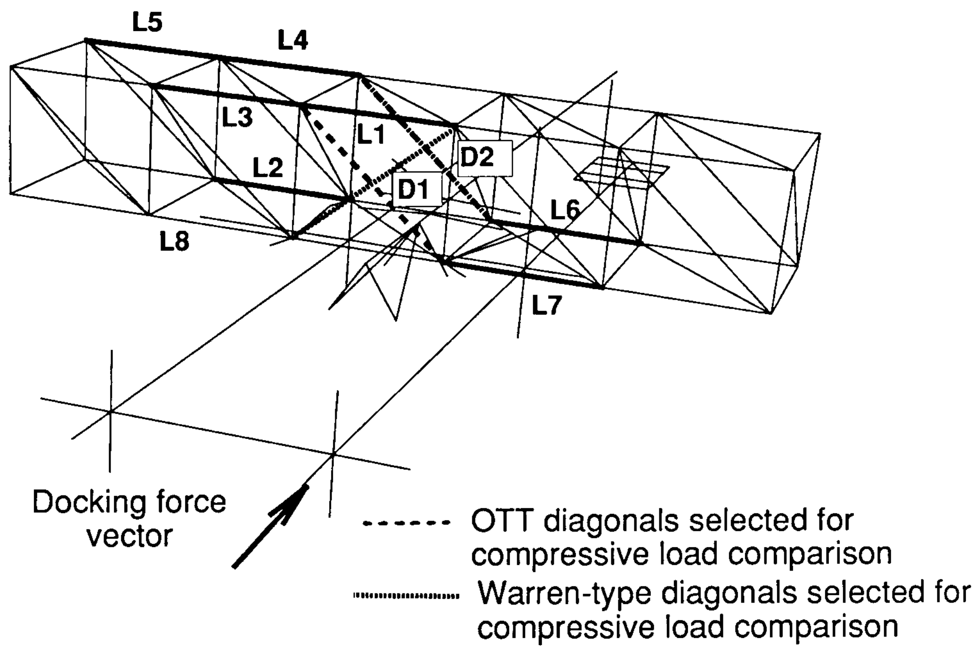


Figure 16. Truss struts selected for compressive load analysis.

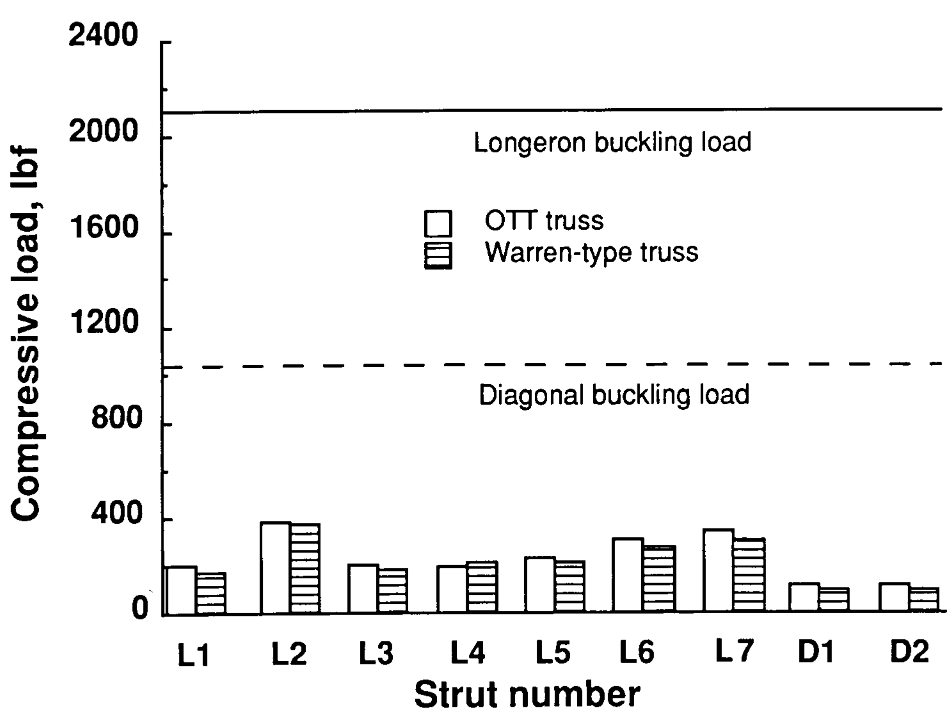


Figure 17. Strut compressive loads due to shuttle docking load.

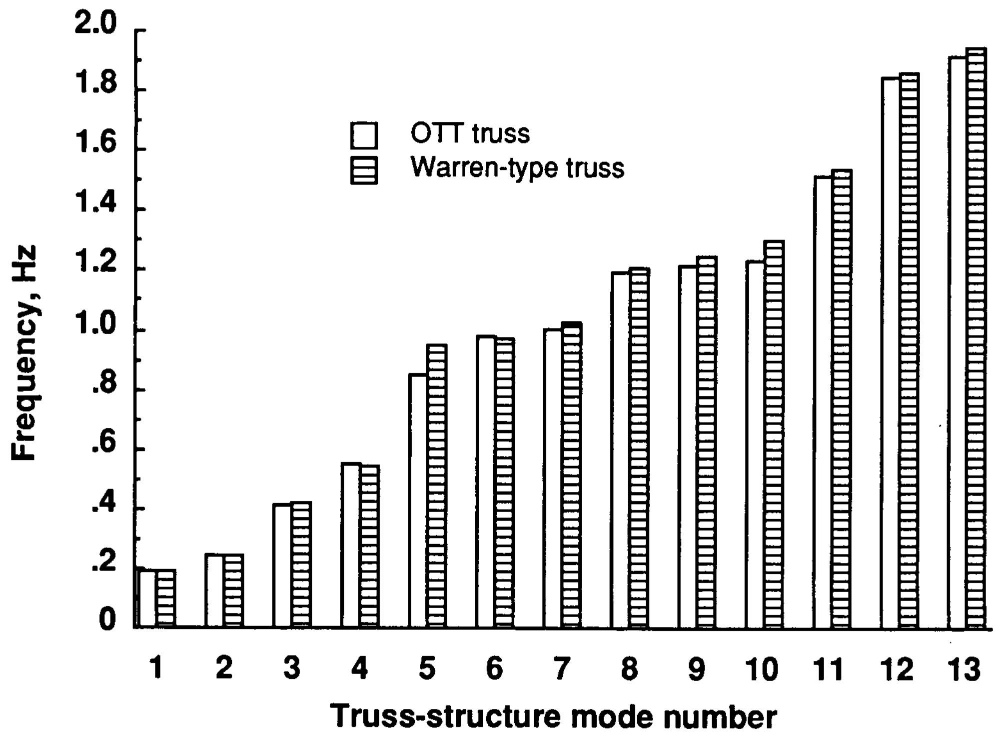


Figure 18. Truss-structure frequencies for space station model with missing longeron L2.

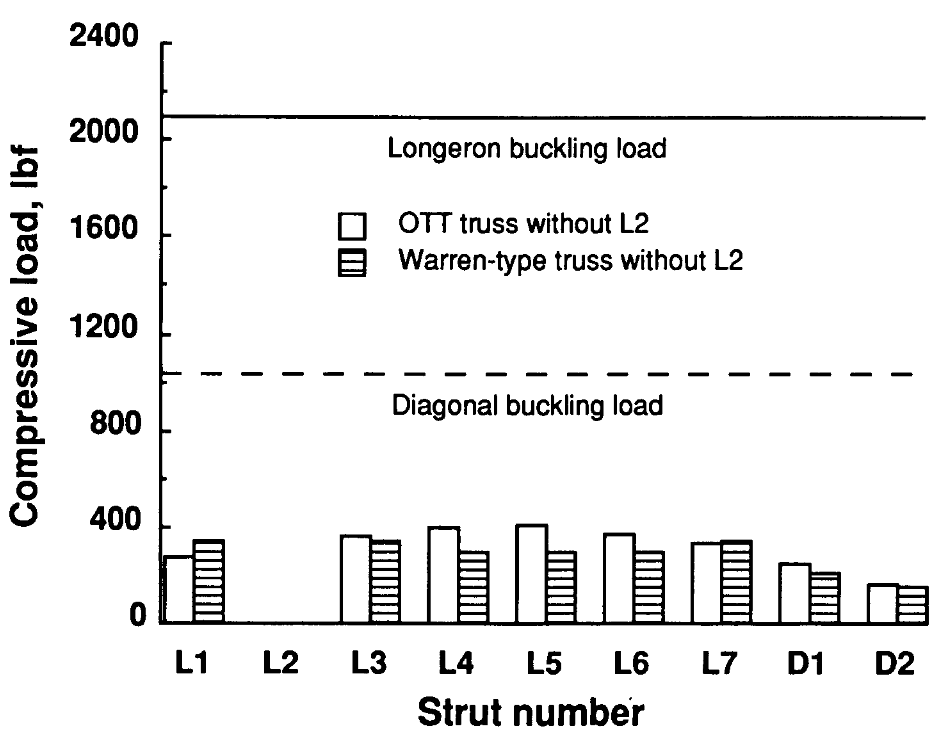


Figure 19. Strut compressive loads due to shuttle docking load with longeron L2 removed.

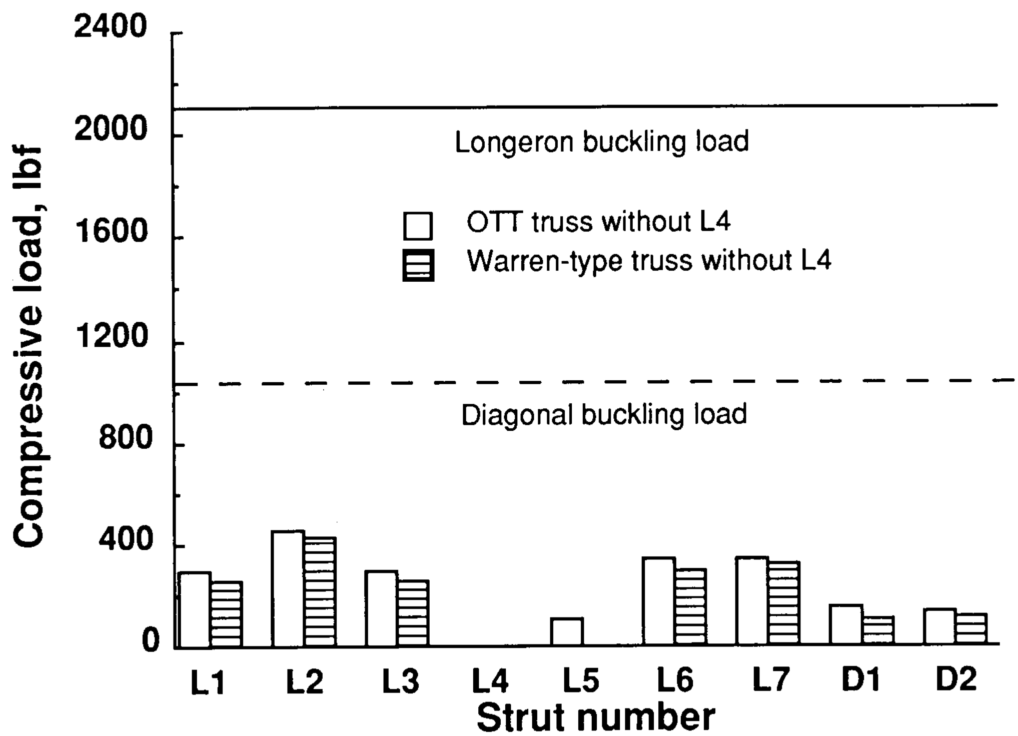


Figure 20. Strut compressive loads due to shuttle docking with longeron L4 removed.

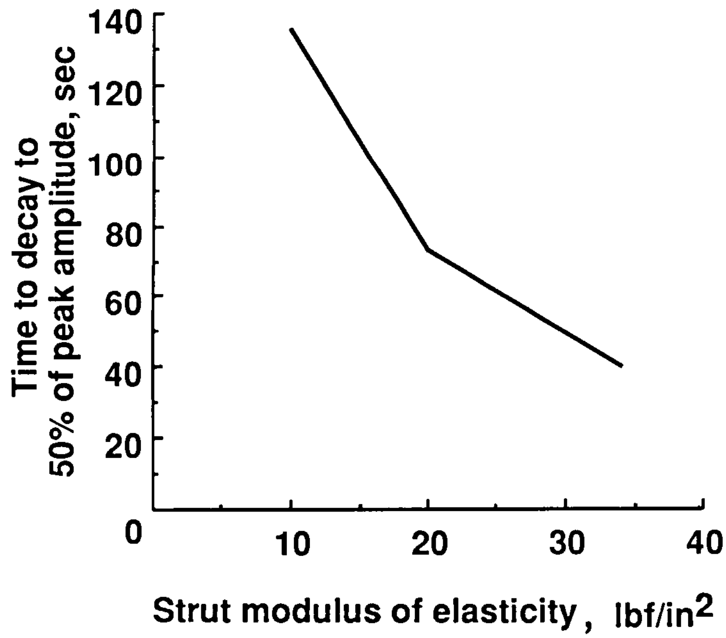
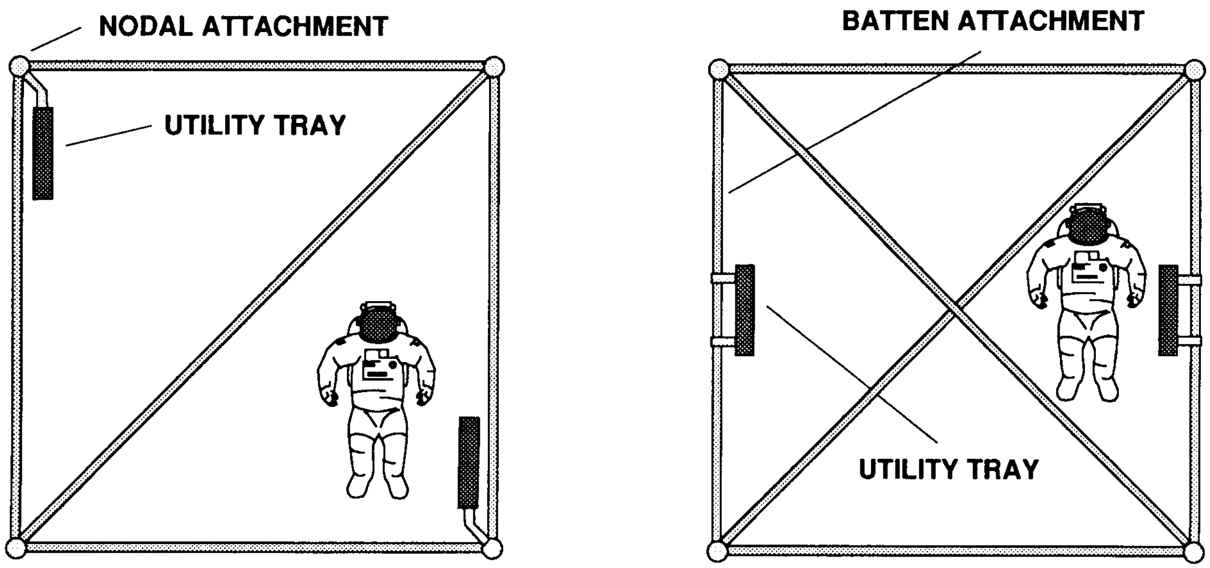


Figure 21. Strut-stiffness effect on response decay time.



(a) Orthogonal tetrahedral (OTT) truss.

(b) Warren-type truss.

Figure 22. Utility-tray connections.

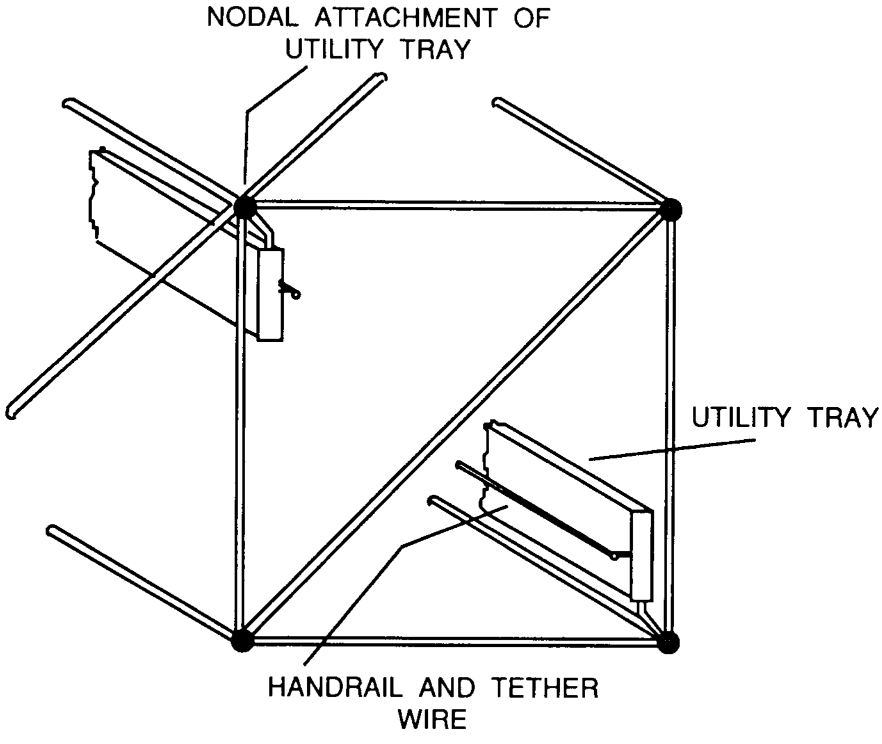


Figure 23. Crew translational aid integrated with utility trays.

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Report Documentation Page

1. Report No. NASA TM-4093	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Comparison of Two Trusses for the Space Station Structure		5. Report Date March 1989
		6. Performing Organization Code
7. Author(s) Thomas R. Sutter and Harold G. Bush		8. Performing Organization Report No. L-16540
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		10. Work Unit No. 506-43-41-02
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The structural performances of two truss configurations, the orthogonal tetrahedral and a Warren-type, are compared using finite element models representing the phase 1 space station. The truss torsional stiffness properties and fundamental torsion frequency are determined using cantilever truss-beam models. Frequencies, mode shapes, transient response, and truss-strut compressive loads are compared for the two space station models. The performance benefit resulting from using a high-modulus truss strut is also presented. Finally, assembly and logistics characteristics of the two truss configurations are evaluated.

17. Key Words (Suggested by Authors(s)) Space station; Trusses; Dynamic characteristics; Assembly considerations	18. Distribution Statement Unclassified—Unlimited. Subject Category 18

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	21	A03

NASA FORM 1626 OCT 86 NASA-Langley, 1989