STRUCTURAL SIZING CONSIDERATIONS FOR LARGE SPACE STRUCTURES

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INTRODUCTION AND OBJECTIVES

A number of missions for the Space Shuttle have been proposed which involve placing large truss platforms on-orbit (figure 1). These platforms range in size from tens of meters in span for reflector application to several thousand meters for solar power collector application. These proposed sizes and the operational requirements considered are unconventional in comparison to earthbound structures, and little information exists concerning efficient proportions of the structural elements forming the framework of the platforms. Such proportions are of major concern because they have a strong influence on the packaging efficiency and, thus, the transportation effectiveness of the Shuttle.

The present study is undertaken to: (1) identify efficient ranges of application of deployable and erectable platforms configured for Shuttle transport to orbit, and (2) determine sensitivity to key parameters of minimum mass deployable and erectable platform designs. The term "deployable" herein is limited to those structures that are manufactured, fully assembled, and folded for packaging in the Shuttle cargo bay on earth so that the complete structure can be unfolded on-orbit. "Erectable" structures would have the individual truss members manufactured and precisely set to length on earth, but not assembled into full platforms until orbit is achieved. Each of these concepts has its advantages and disadvantages, and it is important to know the sizes and applications that may be best suited to deployable construction and those where erectable structures may have the advantage.

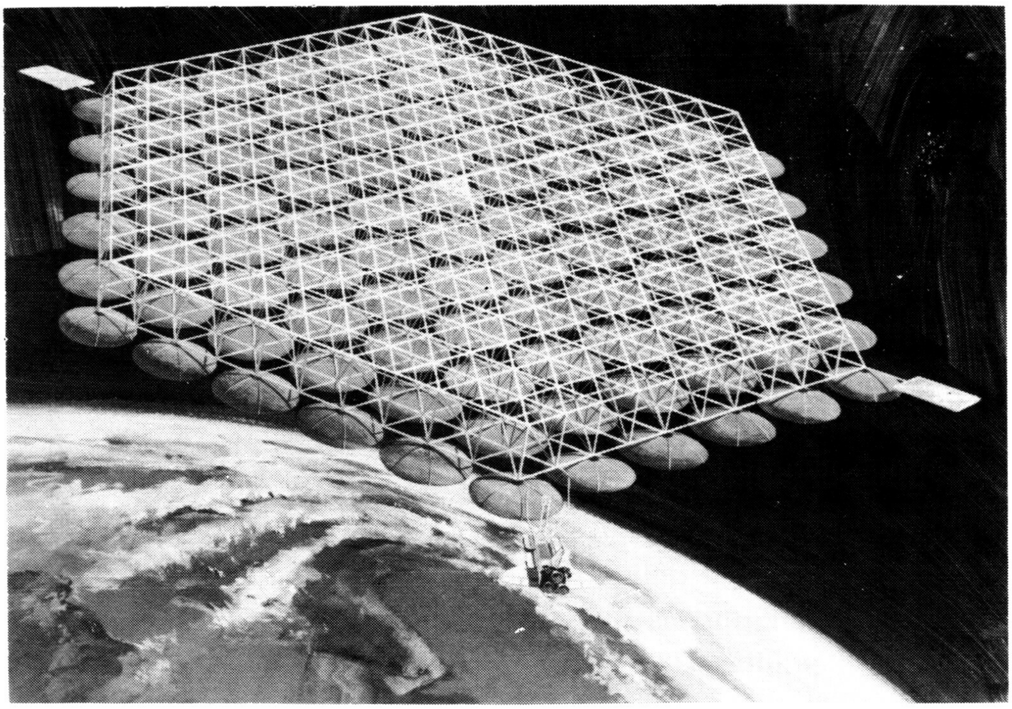
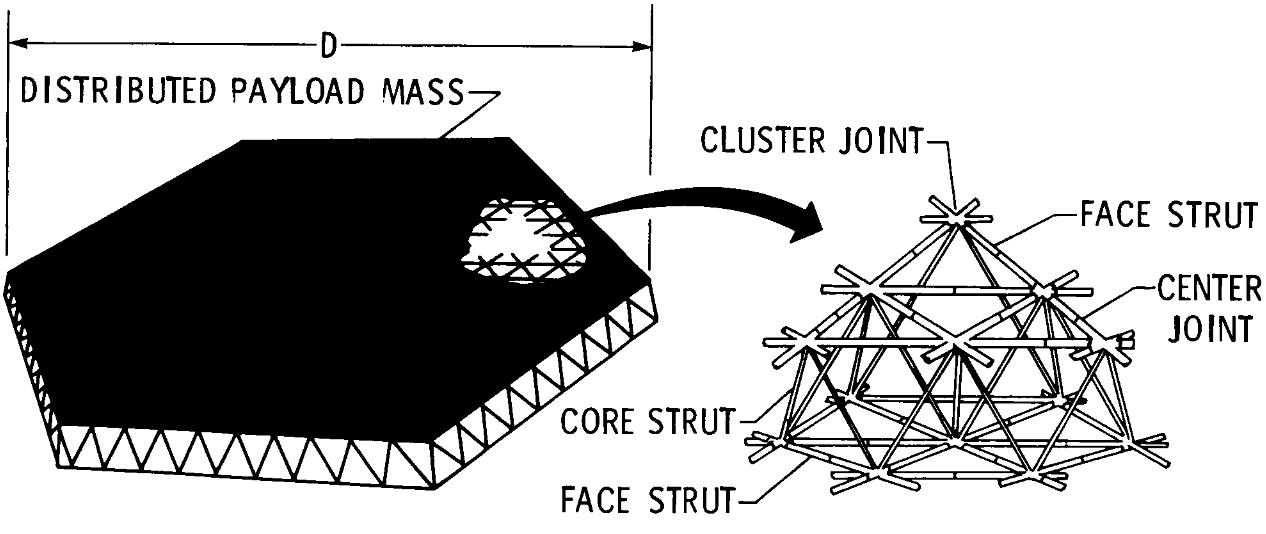


Figure 1

STRUCTURAL CONFIGURATION

To accomplish the objectives the tetrahedral truss was selected as the mathematical model because of its inherent low mass and high stiffness characteristics. Figure 2 describes the structure and the terminology used. The platform has a hexagonal planform of maximum span D. A distributed nonstructural (payload) mass may be attached to one surface. The expanded view in figure 2 shows a cutaway segment of the truss without the surface covering. The platform is constructed of face struts which are the members in the upper and lower surfaces of the platform, and core struts which are the intersurface members. The struts are interconnected by cluster joints which accommodate nine struts per node -- six face struts and three core struts. The face struts may have different geometric proportions than the core struts and may also be of different material. However, all results shown herein are for graphite-epoxy strut material and aluminum joints. Joint masses were assumed to be proportional to strut diameters with mass factors taken from actual laboratory specimens.



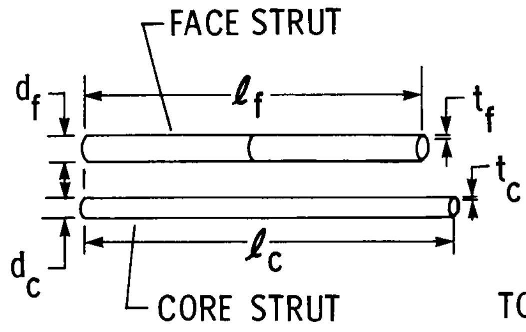
HEXAGONAL PLANFORM

TRUSS SEGMENT

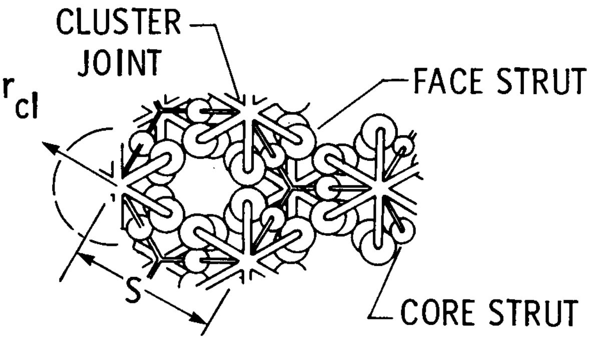
Figure 2

DEPLOYABLE PACKAGING

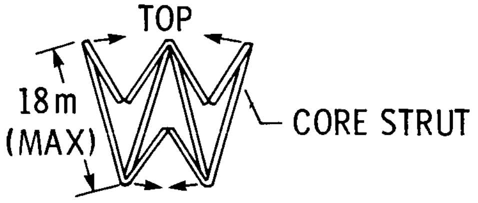
The packaging details for the deployable platform are shown in figure 3; the appropriate equations are presented in reference 1. The deployable platform is assumed to be constructed of cylindrical struts. The face struts are hinged at their centers to fold inward. The core struts are one piece. In this arrangement the face struts can never be longer than the core struts or interference will occur between upper and lower face struts in the folded configuration. The maximum allowable length of the package is taken to be 18 meters, the approximate length of the Shuttle cargo bay. This folding arrangement is usually more efficient than outward folding surface struts because it permits packaging of a deeper and thus a stiffer platform in the Shuttle cargo bay. The cross-sectional area and volume requirements for packaging are functions of six variables -- face strut diameter, length, and thickness, and core strut diameter, length, and thickness.



SIZING VARIABLES FOR STRUCTURAL OPTIMIZATION



TOP VIEW SHOWING PACKAGED TRUSS GEOMETRY

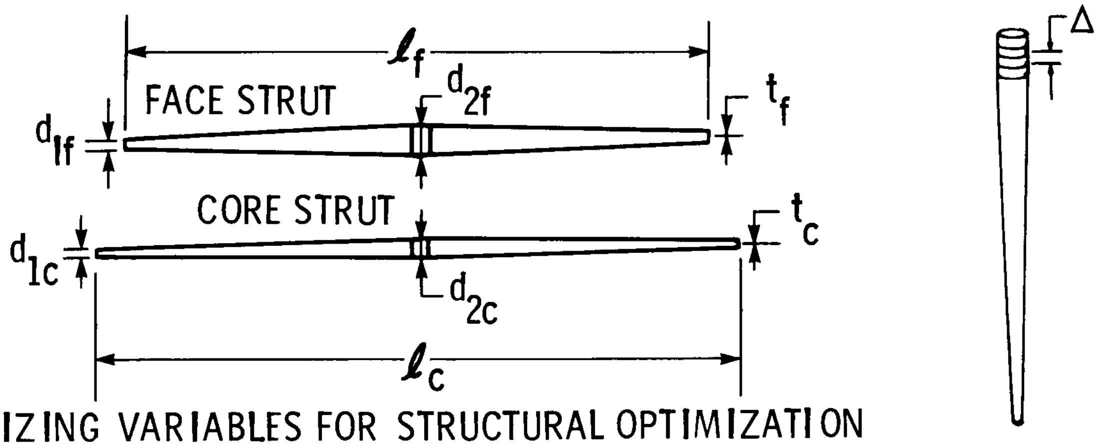


PACKAGE WITH INWARD FOLDING FACE STRUTS

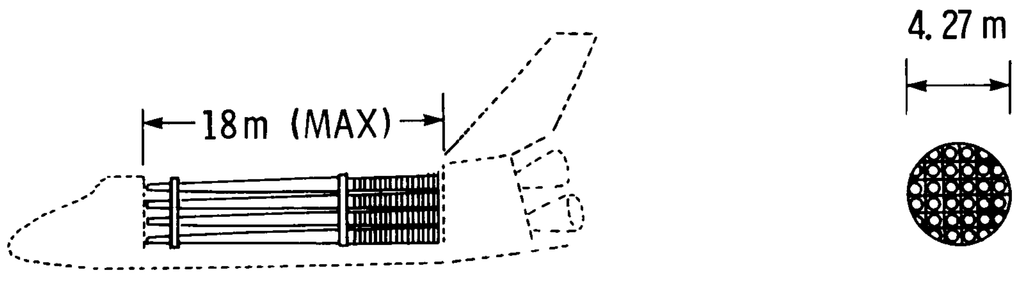
Figure 3

ERECTABLE PACKAGING

The packaging details for the erectable platform are shown in figure 4; the appropriate equations are presented in reference 1. The erectable platform truss is constructed of doubly tapered, nestable, struts which are assembled from two conical strut halves joined at their large ends. The strut halves are nested like ice-cream cones, packed in the Shuttle in stacks of strut halves, and assembled into full struts on-orbit. The stacks of strut halves may not exceed 18 meters in length. A square packing array is assumed for the cross-sectional packaging arrangement of the stacks so that the maximum diameters of the struts determine the approximate cross-sectional area required for stowage. The other variables that determine packaging requirements are thicknesses, lengths, and minimum diameters of the face and core struts -- eight variables in all.



SIZING VARIABLES FOR STRUCTURAL OPTIMIZATION



PACKAGED STACKS OF NESTED STRUT HALVES

SQUARE PACKING ARRAY ASSUMED

Figure 4

STRUCTURAL OPTIMIZATION APPROACH

Figure 5 indicates the approach used to arrive at optimum designs. The objective is to minimize the structural mass per unit area of the platform (ref. 1) with respect to the strut proportions. The minimization takes place subject to any number of design requirements and constraints deemed pertinent to the problem and which can be written analytically. The CONMIN computer program (ref. 2) which uses mathematical programming techniques to solve nonlinear, constrained, optimization problems is used as the structural optimizer.

- MINIMIZE PLATFORM STRUCTURAL MASS PER UNIT AREA,

$$\left(\frac{M}{A}\right)_{\text{PLATFORM}} = \left(\frac{M}{A}\right)_{\text{STRUTS}} + \left(\frac{M}{A}\right)_{\text{JOINTS}}$$

- WITH RESPECT TO STRUT PROPORTIONS,

  THICKNESSES
  DIAMETERS
  LENGTHS

- SUBJECT TO DESIGN REQUIREMENTS AND CONSTRAINTS.
- OPTIMIZER -- CONMIN COMPUTER PROGRAM.

Figure 5

DESIGN CONSTRAINTS

Simple analytical relations are presented in reference 1 for the platform structural response. These relations become the constraints used to size the struts according to specified response standards. For instance, as shown in figure 6, the platform fundamental frequency can be constrained to be greater than or equal to a specified design frequency predetermined to insure sufficient platform stiffness for mission accomplishment. The fundamental frequency of the struts can also be constrained to some multiple value of the platform design frequency. In addition, strut loads arising from a variety of sources can be constrained to be less than or equal to the strut Euler buckling load. Other effects such as initial curvature of the strut axis and strut taper which affect strut axial stiffness and ultimately platform bending stiffness are also considered. Some selected numerical results for tetrahedral truss platforms optimized in this manner are shown in the next three figures.

STRUCTURAL RESPONSE	CONSTRAINT
● f_T, TRUSS FUNDAMENTAL FREQUENCY (FREE EDGES)	$f_T \geqq f_d$
● f_s, STRUT FUNDAMENTAL FREQUENCY (SIMPLY SUPPORTED)	$f_s \geqq kf_d$
● P, STRUT LOAD (SIMPLY SUPPORTED)	$P \leqq P_E$

WHERE

$P = P_d$, CONSTANT DESIGN LOAD (ASS'Y, DOCKING, ETC.)

$= P_{gg}$, GRAVITY GRADIENT CONTROL LOAD

$= P_{ot}$, ORBITAL TRANSFER LOAD

Figure 6

PLATFORM DESIGN FREQUENCY EFFECTS

For the results in figure 7, a distributed payload mass of 0.1 kg/m^2 was assumed. Also, the strut fundamental frequency was required to be at least 10 times the platform design frequency. The results in the left-hand plot in figure 7 show that the mass per unit area of efficient deployable and erectable platforms is comparable over the range of design frequencies investigated, and that platform frequency has a very strong influence on the structural mass requirements (nearly proportional). Note also that the structural mass per unit area values for efficient platforms are very low -- on the order of a mesh reflector surface-covering.

The effect of platform design frequency on Shuttle transportation requirements is shown in the right-hand plot in figure 7. In the lower frequency range, the number of Shuttle flights required to orbit erectable and deployable platforms of a given size is similar. In the higher frequency range, Shuttle flights increase sharply for deployable platforms while erectables exhibit a more gradual increase. This is because at the lower frequencies, the packaged platforms are mass controlled Shuttle cargos. At higher frequencies erectable platforms remain mass controlled cargos, but the deployable platform packages become volume controlled cargos. These results indicate that for a given size platform, there is a practical design frequency (i.e. structural stiffness) upper limit for deployable platforms, above which transportation costs will become increasingly prohibitive.

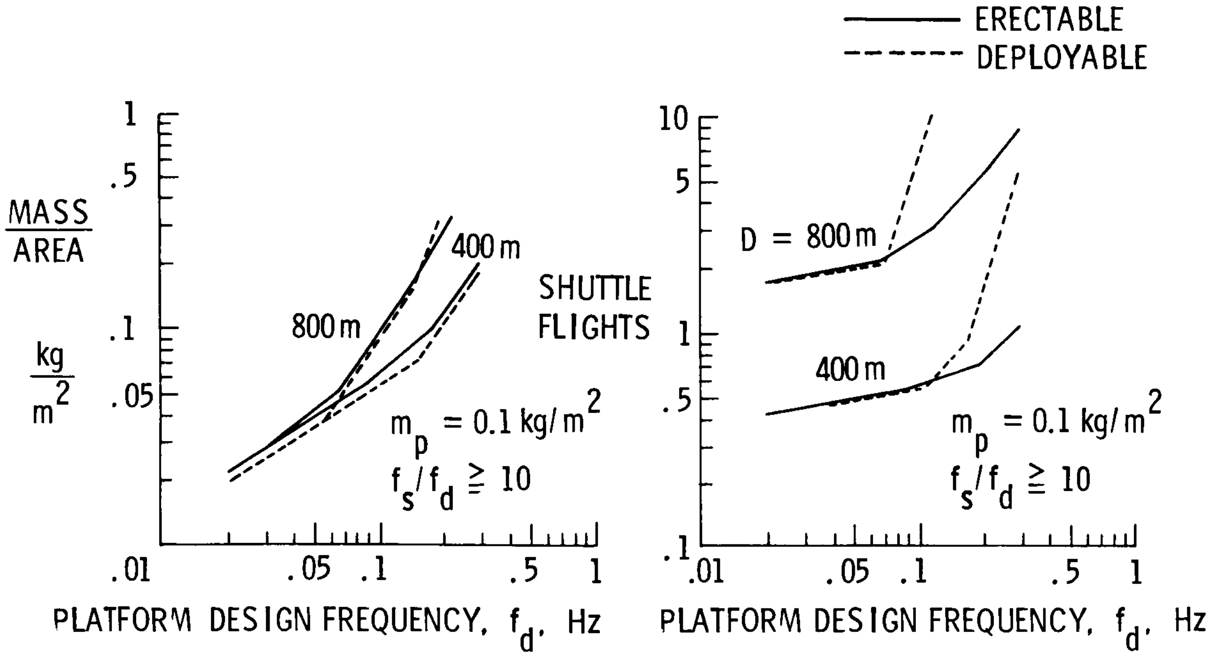


Figure 7

STRUT DESIGN FREQUENCY EFFECTS

For the results shown in figure 7 the strut frequency was specified to be at least ten times the platform design frequency. The effect of relaxing this requirement is presented in figure 8. Results are shown for both 800 and 400 meter erectable and deployable platforms, designed for a .1 Hz fundamental frequency. Again, the payload mass is assumed to be .1 kg/m^2. The left-hand plot in figure 8 shows that the mass per unit area requirements at the strut frequency factor of ten are approximately four-to-five times greater than that for a frequency factor of two. This indicates that strut frequency factor is a strong structural design driver (mass per unit area requirements are nearly proportional to strut frequency requirements). The right-hand plot shows that the Shuttle flights required by the 400 meter platforms are not greatly affected by the strut frequency factor over the range investigated. However, an abrupt increase in Shuttle flights occurs for the 800 meter deployable platform above a strut frequency factor of five indicating that practical limits for this parameter also exist for large deployable platforms.

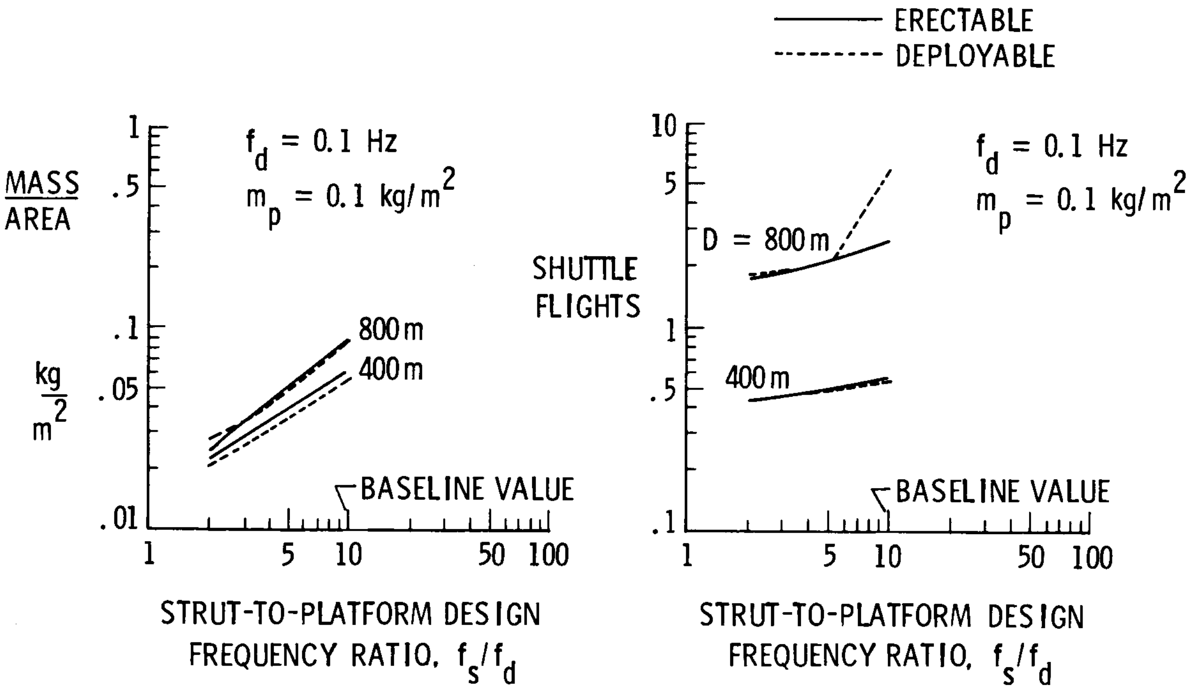


Figure 8

STRUT DESIGN LOAD EFFECTS

Figure 9 shows the effect of a constant strut design load on mass and transportation requirements. The range of design loads considered is from 10 to 400 Newtons. Again, calculations are for a payload mass of .1 kg/m^2, a .1 Hz platform design frequency, and a strut frequency factor of ten. The structural mass per unit area requirements shown in the left-hand plot in figure 9 are not greatly affected over the load range considered except for the 400 meter deployable platform which shows about a factor of two mass increase. The right-hand plot shows that Shuttle transportation for erectable platforms (solid lines) is also relatively unaffected over this load range. There is, however, a significant impact of strut design load on the Shuttle transportation for the 400 meter deployable platform. Transportation requirements increase from .5 flights, for essentially zero design load, to approximately four flights for a design load of 400 Newtons. (The increased strut cross-section required to carry the design loads causes a factor of eight packaging penalty on the 400 meter deployable platform). The transportation requirements for the 800 meter deployable platform indicate that the larger strut cross-sections required to satisfy frequency constraints are sufficient to carry strut loads up to approximately 80 Newtons. Above this value, strut cross-section increases significantly to carry the load, as shown by the increased Shuttle flight requirements -- about a factor of two over the range of loads investigated.

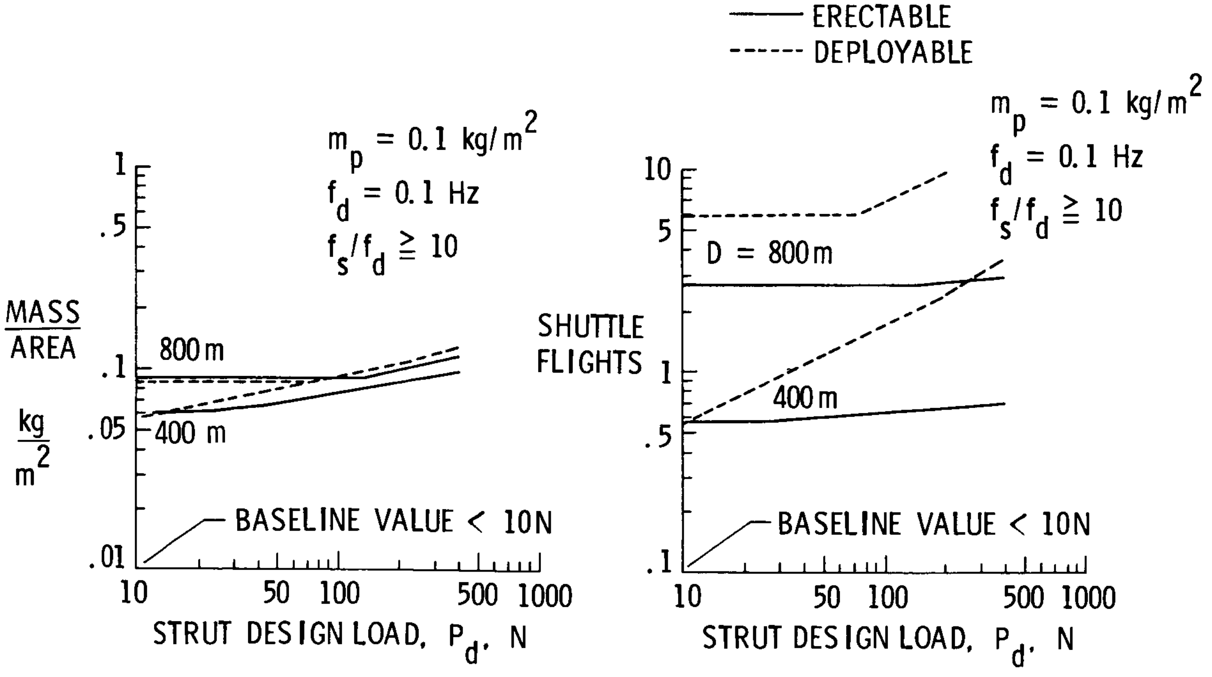


Figure 9

TRANSPORTABILITY OF SLENDER STRUT DEPLOYABLE PLATFORMS

The structural proportions which characterize minimum mass truss designs are extremely important, particularly for deployable trusses (ref. 3). Conventional truss structures typically employ struts having slenderness ratios (ratio of strut length to radius of gyration) less than 300. The platform designs presented herein exhibit strut slenderness ratios ranging from 600 to 4000, and still satisfy all imposed design requirements.

The benefits of slender strut construction are illustrated in figure 10, where the Shuttle flights required to orbit various size platforms are given as a function of the optimum strut slenderness ratio. For these calculations the payload mass, m_p, is .1 kg/m^2 and struts are constrained to have a fundamental frequency of at least ten times the platform fundamental design frequency. The curves for each platform size are the loci of minimum mass designs and encompass an approximate range of platform design frequencies from .04 Hz to .28 Hz. For a given size platform, as slenderness ratio increases (and frequency decreases) the Shuttle flights required to transport that platform to low earth orbit decrease rapidly. Each curve exhibits an abrupt change at an approximate slenderness ratio value of 1600. At slenderness ratios less than this value, Shuttle flights of deployable tetrahedral trusses are volume controlled; above this value they are mass controlled for the design requirements considered in this study. The potential benefit of reducing the number of Shuttle flights required to orbit a large deployable platform (e.g. antenna or collector surface) is sufficiently attractive to warrant a thorough investigation of slender strut construction of large truss platforms.

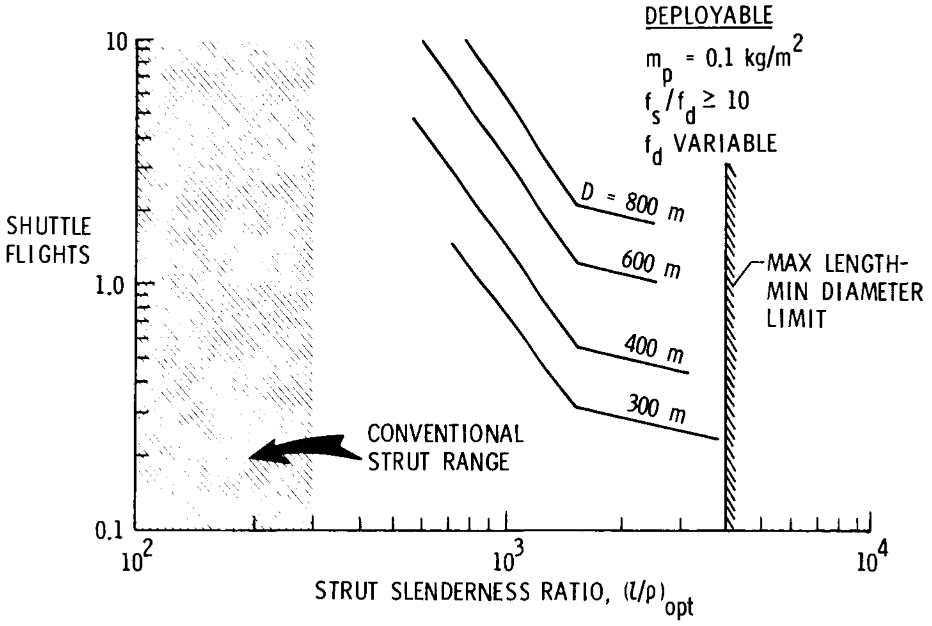


Figure 10

ORBITAL TRANSFER OF DEPLOYABLE PLATFORMS

All results shown in the previous figures have been for platforms sized for low earth orbit operation. If these platforms require subsequent transfer to geosynchronous orbit for mission accomplishment, they must be sized to withstand the acceleration loads for this maneuver. For an initial assessment of orbital transfer loads, the effects on deployable platform transportation requirements were examined and results are shown in figure 11. The study is limited to considering only constant thrust chemical propulsion systems. The propulsion system thrust load is applied normal to the surface of the platform at the three centermost cluster joints. Deployable platforms of 100, 150, and 200 meter spans are sized for thrust-to-weight ratios ranging from .001 to .1 g's. The results show only the number of Shuttle flights required to place a platform sized for these thrust loads into low earth orbit. The transportation requirements for orbiting the propulsion system to send the platform on to geosynchronous orbit are not shown. For the conditions specified, these results indicate that the maximum size platform that could be placed in GEO, using one Shuttle flight to LEO, is approximately 200 meters in span using a thrust-to-weight ratio of .01 g. The maneuver would take about 15 hours. A faster transport time for a 200 meter platform would require heavier struts to carry the larger acceleration loads, thus multiple Shuttle flight would be required to orbit the larger package.

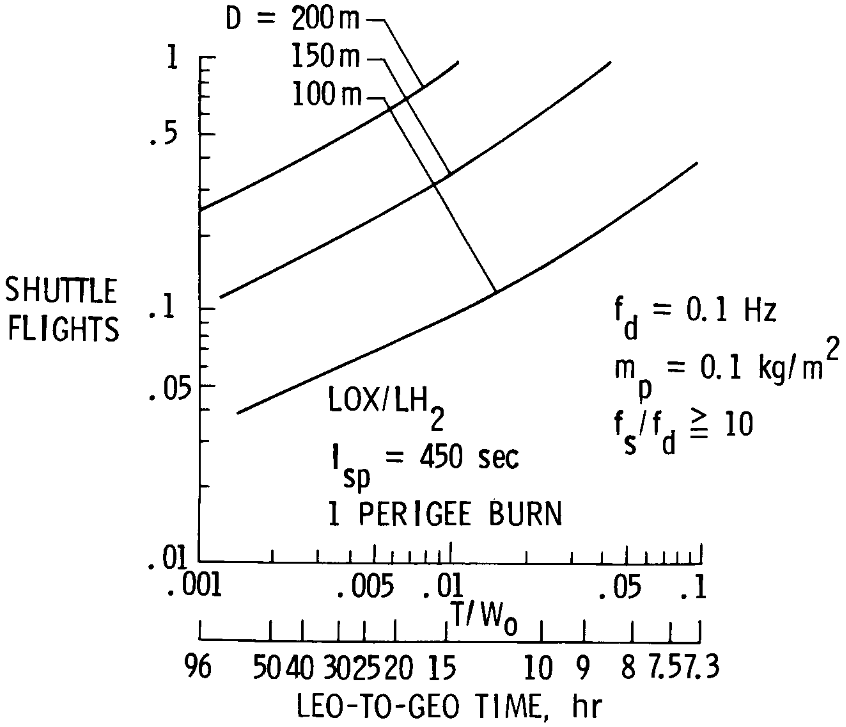


Figure 11

CONCLUDING REMARKS

Large deployable and erectable tetrahedral truss platforms are sized for minimum mass to meet a variety of practical design requirements using computerized mathematical programming techniques. These platform designs are characterizd by ultra-low structural mass per unit area which is equivalent to that of mesh reflector surfaces.

The struts for minimum mass deployable and erectable truss platforms are found to be much more slender than struts conventionally used for earthbound structural applications. The transportation efficiency exhibited by platforms constructed of these slender struts warrants a thorough investigation to determine the feasibility of fabricating spacecraft in this manner.

Platform fundamental frequency, which is a measure of overall structural stiffness, is shown to be a strong design driver, indicating a need to determine the minimum acceptable value of this parameter which will permit mission accomplishment. The severe effect on structural proportions of maintaining high strut frequency relative to platform frequency also indicates a need to determine the minimum value of this parameter required to prevent vibrational coupling between strut and platform.

Preliminary orbital transfer investigations indicate that deployable platforms of up to 200 m span may be placed in geosynchronous orbit with a single Shuttle flight using a constant thrust chemical propulsion system which limits initial acceleration to .01 g or less.

- EFFICIENT DESIGNS EXHIBIT ULTRA-LOW STRUCTURAL MASS
- STRUT SLENDERNESS RATIOS MUCH GREATER THAN CONVENTIONALLY USED FOR EARTHBOUND STRUCTURES
- PLATFORM AND STRUT FREQUENCY REQUIREMENTS ARE STRONG STRUCTURAL DESIGN DRIVERS
- HIGH STIFFNESS REQUIREMENTS LIMIT THE RANGE OF APPLICABILITY OF DEPLOYABLE PLATFORMS
- PLATFORMS OF UP TO 200 m SPAN, SIZED FOR ORBITAL TRANSFER TO GEO, REQUIRE ONE SHUTTLE FLIGHT TO LEO

Figure 12

REFERENCES

1. Heard, Walter L., Jr.; Bush, Harold G.; Walz, Joseph E.; and Rehder, John J.: Structural Sizing Considerations for Large Space Platforms. AIAA Paper No. 80-0680, presented at the AIAA/ASME 21st Structures, Structural Dynamics and Marterials Conference, Seattle, WA, May, 1980.

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