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Efficient Satellite Structural Design Optimised for Volume Production**Angelos Tsinas**

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Abstract:

In the past, the limited number and production volume of satellites has meant that their structural design has been essentially a one-off procedure. As a result, the most common choice of primary structural medium has been metal. Although eminently reliable and highly proven, this option has led to a comparatively high structural mass fraction of 20-24%.

The emergence of communications satellite constellations creates the need for a complete reappraisal of current design practices. Emphasis needs to be given in the implementation of volume production methods, already matured through experience in the aviation industry, to manufacture of satellites. The prospect of new materials and technology can offer reductions in the overall structural mass of satellites in the region of 15-20% which in turn can lead to significant overall mass savings and reduced launched costs. However the aim of mass reduction can only be appreciated in terms of total cost savings, i.e. the net balance of the mass savings versus the technological application cost should be positive.

This paper describes current approaches to the design of volume production satellites such as Technological Islands, Virtual Factory, Multifunctional Surfaces, Short Accelerated Production of Satellites (SNAPSAT) in respect of efficiency and economy. The implementation of volume production methods such as JIT and Taguchi in the area of satellite technology is also examined.

Alternative designs for mass production satellite structures are considered. Ideas described include a conventional truss of both composite and aluminium manufacture and a corrugated plate modelled upon the multifunctional surface.

**Satellite Structures
Manufacturing Issues*****Past Practices***

In the past, satellite projects have been characterised by a limited production runs. The bus structure used to be mainly metallic, typically of a honeycomb or monocoque thrust tube and surrounding shear panels. This in essence translated in an increased part count (especially in forms of connectors and fasteners),

resulting in a high cost and an increased percentage of the structural mass as part of the total mass. This weight allocation, although unavoidable, was responsible for increased launch costs, which were more profound for GEO launches. Furthermore, even for quite successful designs such as the HS-601 GEO families, the need for volume production methodology was offset by the large number of different projects. This resulted in a small procurement number per order so that the cost per bus remained high.(1)

Modern Constellations and the Need to Devise New Methods of Manufacture

Most modern satellite constellation designs feature a dense network of LEO satellites in order to achieve the desired Earth coverage. The choice of LEO is made on the grounds of a better signal quality with minimal signal latency, reduced launch costs and the need for a more compact and economical satellite in terms of size, mass and power allocation. Also the use of new materials, culminating in the introduction of the composites and exotic alloys results in extremely high specific strength values which can offer flexibility and, potentially, offer significant cost savings.

Volume Production Methods

Just In Time

Just In Time (JIT) is a systems approach to developing and operating a manufacturing system, based on the concept of waste elimination. (2) It requires that equipment, resources, and labour should be readily available in the correct amounts required at any current moment. Its fundamental principle is that only the necessary units and the necessary quantities should be manufactured. This is achieved by constant monitoring of the production rate and adjustment for production needs. Besides waste elimination, the benefits of JIT are increased productivity, work performance and product quality while enabling low cost.

Aspects of JIT include:

- Integration and Optimisation
- Quality Control
- Reducing Manufacturing Cost
- Producing Product on Demand
- Developing Manufacturing Flexibility
- Establishing Links with Customers and Suppliers

The main requirements to be fulfilled in order to successfully implement JIT are:

- Partnerships
- Commitments
- Contracts Supporting Partnerships
- Developing JIT suppliers
- Customer-Supplier proximity

It is apparent that conventional manufacturing methods can't be implemented in such cases because of the increased manufacturing costs, pressing project completion timescales, and unacceptably high launch costs. The solution should come by mimicking successful volume production methods similar to these implemented in other high technology industries such as aeronautical, automotive and electronics engineering. The difference, of course, is to be found in the absolute magnitude of the numbers produced. However in aspects such as project management the situation is comparable. The implementation of modern production methods in the satellite industry was a first step to a new direction and has not yet fully matured. The next section describes most of these methods and gives relevant examples of current practices when applicable.

Taguchi Methods

Dr. Taguchi played an important role in shaping the attitude and philosophy of the Japanese industrial and manufacturing strategy after the Second World War, which led to the economic growth and development of Japan. While Western attitude was focused on increasing output rate, Taguchi introduced the concept of Total Quality Management (TQM) in order to maximise profits. The definition of quality is based on whether the product is able to fulfil its specified mission at the least cost. (3)

The space industry was late to adopt Taguchi principles, because of the low production numbers of spacecraft families. However, the emergence of communication satellite constellations projects has created the need for a different approach to the issue of manufacture of satellites. Indeed, both NASA and the Department of Defence in the US, and their counterparts in Europe and Japan have started to establish TQM practices in their projects, focusing on the relationship of performance with respect to development cost. This attitude could be summarised as "Cheaper, Smaller, Faster", allowing the rapid development and deployment of new projects.

The core of TQM is that quality should be achieved at the design level of the project. Once the product goes into production, any modifications result in additional cost and time delays. Achieving quality control is accomplished by any of the following three means:

1. System Design: System design ensures that the product is built according to strictly laid down specifications. Consequently, the outcome is a project of increased reliability (but at a higher cost, which may deter potential buyers).

2. **Parameter Design:** In parameter design, the factors that influence the performance are monitored and weighted. As a result, the strong and weak points of the design are found and areas of specific consideration and interest are located. The ability of the product to resist the influence of the external parameters is defined as “robustness”, and the result as achieving a “robust design”. The comparison of the influencing parameters is accomplished using “orthogonal arrays”; a form of matrices, which allow a quality score for every modification, thus allowing the selection of the most suitable
 - Design the Matrix Experiment and establish the Data Analysis Procedure
 - Conduct Matrix Experiment
 - Analyse Data and Determine Control Factors’ Optimum Levels
 - Predict Level’s Performance
3. **Tolerance Design:** Accepting wider tolerances in design allows the manufacture of a cheaper product at the price of reduced reliability and vice versa. Concluding, it could be said that Taguchi method dictates that quality control efforts should begin at the early stage of design process, in order to conceive a configuration that is less prone or more robust to external influences, allowing for a reasonable cost.

Benefits of the Taguchi approach, therefore, include time and resource savings, parameter influence identification in terms of operation performance and cost. This allows effective allocation of resources and time, which translates as low cost, high quality solutions.

Virtual Factory

“Virtual factory” is a term coined by the Iridium company in order to describe the operational procedures and methods that were applied in the Iridium project.

The definition of virtual factory is: “ *A team of multiple companies, each having a distinct world class core competence, that are leveraged in a partnership through collaboration and teamwork, resulting in a distinct competitive advantage.*” (4)

The main issues that a virtual factory approach has to address are the compatibility and commonality of

candidate. The external influence parameters are defined as “noise”.

The process for a Taguchi optimised design has the following steps:

- Determination of the Quality Characteristic to be Optimised
- Identify of the Noise Factors and Test Conditions
- Identify of the Control Factors and their Alternative Levels

metrics and procedures between vendors and subcontractors; the establishment of good relationship based on trust, a well-established transportation and delivery system etc. Proximity of the installations is an important parameter, but can be compensated by the establishment of effective transportation and the assurance of total quality before the ordered product leaves the “sub-factory” facilities.

Indeed, although Iridium’s components came from a variety of sources in terms of origin and location, all the main assembly and testing was carried out at Motorola’s facilities in Sunnyvale, CA. The level of testing was limited to the subsystem/ complete satellite level, as all component testing is the responsibility of the subcontractor or vendor.

Systems established during the implementation of the “virtual factory” approach included Six Sigma Quality, Design for Manufacturability, and Discrete Event Simulation. During the Process Development and Verification phase, the Iridium partnership established a Quality System Review in order to assess and control the overall quality and performance of the system. Quality was achieved and monitored through a set of processes including Design of Experiments, Statistical Process Control etc.

Technological Islands

The introduction of the LEO communication satellite constellation concept has significantly altered aspects of satellite manufacture. In particular the increase in production demand in a relatively short time scale has proved that the traditional linear manufacturing approach is no longer in position to comply with the requirements.

As a result, a new approach to Assembly, Integration and Test has had to be sought.

For Globalstar, Alenia’s response to this is based on the concept of technological islands, which is defined as “*Areas in the factory where a series of*

homogeneous activities are performed in a well-established and controlled fashion.” (5)

At Alenia, two separate production lines were established for the Globalstar production, with eight islands each dedicated for spacecraft assembly and antenna manufacturing and integration.

Satellite Islands

- Propulsion Assembly Integration and Testing
- Bus and Payload Integration
- Alignment verification
- Satellite performance test and thermal cycling
- Vibration test and solar array installation and deployment
- Mass properties
- Packing and shipping
- Troubleshooting

Antenna Islands

- Antenna pre-assembly
- Hard line test
- Final integration
- Thermal cycling
- Vibration testing
- Near field test range
- Far field test range
- Troubleshooting

The eight production islands are arranged in the Alenia’s Small Satellite Centre manufacturing site based on the following parameters.

- The spacecraft is the only item that moves along the production process.
- No equipment transfer from one island to another is necessary.
- No personnel transfer from one island to another is necessary.
- No backward movement along the production process is necessary.

The use of technological islands requires the need for an extensive and reliable data management system. This allows the support and monitoring of all production activities, while it is integrated with testing, documentation and resource management software for complete process control.

The whole manufacturing process can be monitored at any time and any bottlenecks can be quickly inspected and corrected. The use of integrated

simulation and production flow methods, played decisive role in allocating resources and finance as well as establishing the manufacturing practices in each stage of the production and formulating an optimal process and method of work for each island allowing high efficiency levels.

Each island is responsible for its own production and quality control of the finished product, while the parallel method of manufacture ensures that production flow is kept to the optimal rate through the use of JIT methods. The autonomy of the concept allows for reduction of time delays or disruptions, while any source of error can be discovered and eliminated, if not in the early stages, then before it can infiltrate the production chain.

The factory layout is shown in Figure 1. The Technological Islands Conceptual Organisation and Flow is shown in Figure 2

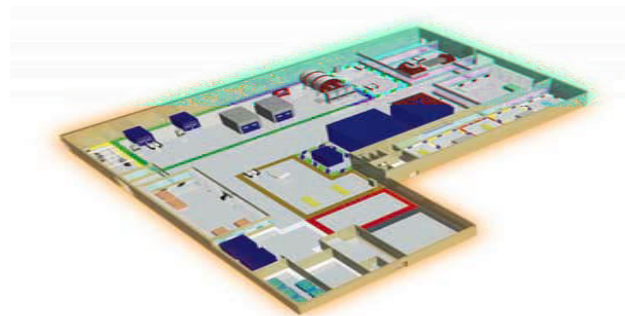


Figure -1 Technological Islands Layout. (5)

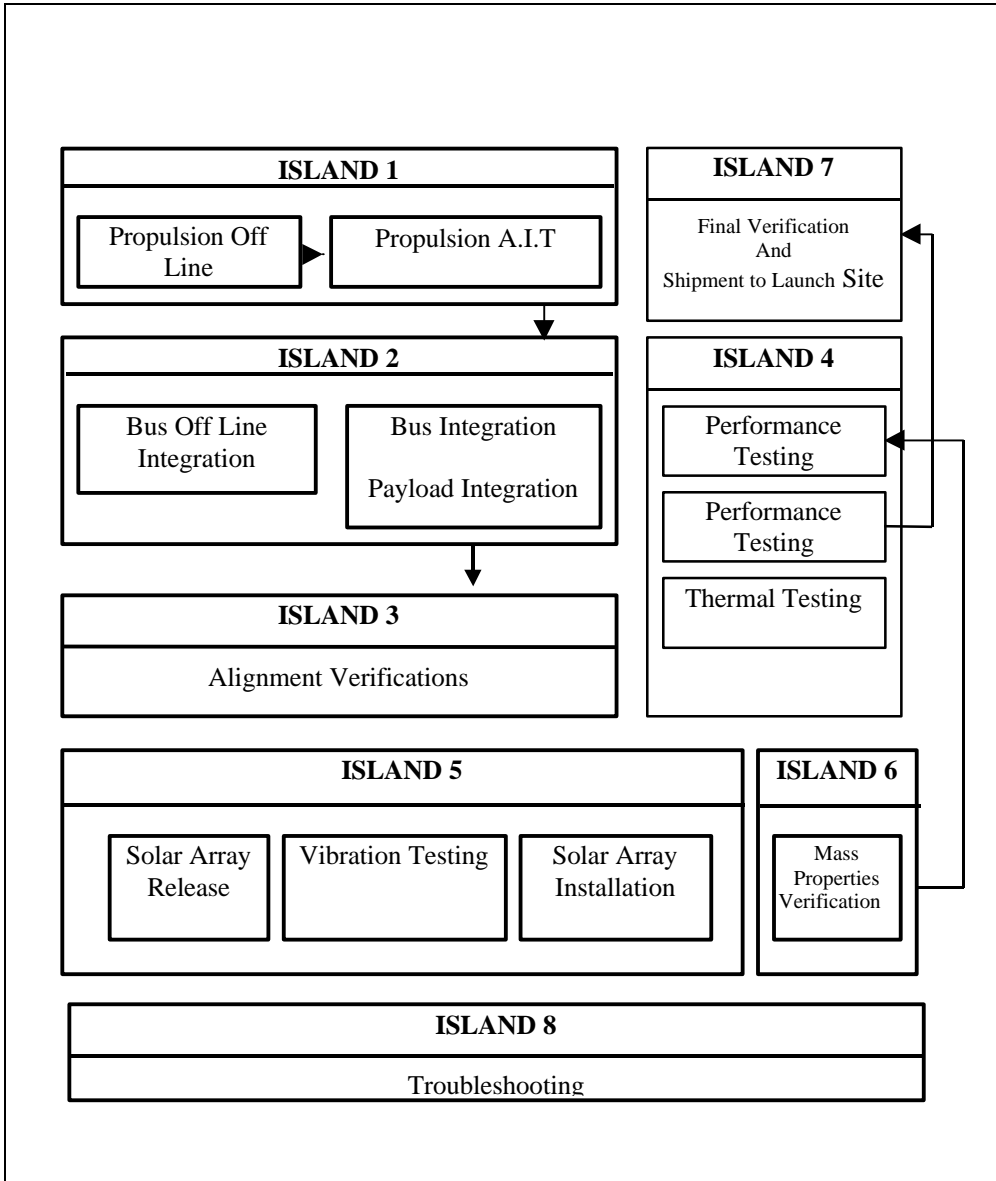


Figure 2 Alenia Factory Island Interactions (5)

In order to control the production schedule Alenia has implemented a Data Management System (DMS), which assures compatibility and ease of communications between Alenia and the other Globalstar, partners. DMS is an extensive Information System which enables the Small Satellite Centre to automatically and in real time receive, categorise, store, retrieve, process, modify and distribute data. Data that may be processed includes drawings, parts lists, material lists, processes and procedures, specifications and results etc. DMS facilities exist for every island, allowing rapid communication, and data exchange within the limits of the factory and external contractors.

SNAPSAT

SNAPSAT (Short Notice Accelerated Production for Satellites) is a relatively new technique devised by COI (Composite Optics Incorporated), for the manufacture of the FORTE satellite. (6) Although limited data has been published, it has emerged that a set of disciplines has been devised and implemented throughout the process, emphasising simplicity and low cost development.

The main structural components are produced from a single laminate plate although the same plate may contain different parts. No mould process is required, and components are cut to appropriate shape by the use of waterjet, or potentially laser. Both options have potential benefits and drawbacks.

The implementation of computer-controlled process for the design and manufacture allows a uniform quality output that can be easily controlled and adjusted according to the incoming needs. Tooling minimisation yields low cost due to the reduction in the non-recurring costs, less testing needs due to reduced part variation and part count, and reduced development time due to automation.

Group Part Process (GPP) is an important parameter in the SNAPSAT method. GPP allows the simultaneous treatment of different shaped parts originating from the same initial plate. Further processes include the adaptation of advanced adhesive dispensing methods allowing reliable and simultaneous bond cure.

Grastataro (7), indicates that the implementation of SNAPSAT principles during the design of FORTE satellite allowed the manufacture of a bus structure at 40% of the cost of an equivalent conventional composite structure, and 25% more expensive than an equivalent metallic structure. Krumweide (8) estimates the actual price at \$160,000, \$400,000 and \$133,000 respectively. Respective weights are 42.6

kg, 42.6 kg and 64.4 kg. Cost in terms of \$/kg are 3750, 9400, 2060 respectively. Another important issue addressed is that of manufacturing lead times, which stand at 10 weeks for FORTE, 16 weeks for the aluminium structure and 30 weeks for the conventional composite structure.

The benefits behind SNAPSAT are based on the simplicity of the manufacture of the structural components and the reduction in manufacturing lead times and overall weight savings, which result in significant cost savings. The potential of the application of the SNAPSAT technology to the manufacture of the next generation of volume produced spacecraft is great, although COI had no plans of initiating a production run.

The shape restriction imposed by the single flat-stock panels could be a potential disadvantage, but it could be argued that most of contemporary volume produced satellites exhibit a simple structural configuration based on reducing part count and complex geometry. On both accounts, the application of SNAPSAT is compatible to the desired properties. The possible drawbacks of this process are shape restrictions. Only flat surfaces are possible, during machining and cutting delamination of the composite layers may occur as a result of improper waterjet or laser beam use. The cutting area may be affected either by the water moisture of the waterjet or the heat of the laser as well as by improper drill speeds. Another disadvantage is an excessive amount of waste material as a result of the cutting technique; therefore, there is comparatively low ratio of utilised/raw material.

A single plate provides less material cost in terms of manufacture or acquisition as well as testing. Whole structural components are made as one-piece components, permitting fewer and well-controlled component parts. Mass production quality is guaranteed through repeatability and fast production rate is achieved. Tooling costs are kept to a minimum, as there is no need for unique moulds and equipment is needed, in fact, the main processing tool is a cutting device, either laser or waterjet to a simple Gerber knife and drills.

However due to the fact that the price of the material in plain plate form is low compared with the price to develop a fully processed component by following more efficient and thus complex methods compensates for material loss. Single plate cut permits the manufacture of whole structural components as one piece, thus saving tooling costs and processing time but also is damage prone in the sense that damage in one member may lead to

scrapping of the whole component.

The benefits of a single plate make it quite attractive for volume production of satellites and it is one of the strongest candidates. The fact that in a truss shape structure load path analysis is quite simple and straightforward reduces the need for additional load tests if the truss has been used before. The problem is then changed if the material can withstand these loads, which is simply an iteration/optimisation process using a typical FEA package.

Structural Options

Truss

A typical truss consists of a large number of different structural members. It is of rectangular, triangular or polygon shape, although the efficiency of the structure drops as the number of corners increases. For many years, the truss has featured very heavily in satellite bus design.

A typical truss is constructed from extruded tubes of variable or uniform cross-section, usually square or cylindrical or separately machined members of an open section such as I, Z shapes. The main materials used for the construction of truss members are light metal alloys, primarily aluminium alloys or composites which combine the need of high stiffness and low density.

The main attachment methods are fasteners, welding, and adhesives. If composite material is to be used for members then the use of metallic, mainly titanium, inserts/ end-fittings is required. Joints in the form of fasteners result in an increase of total structural weight, large part count, and high cost in terms of labour and manufacturing time. It is the aim of the designer, therefore, to find ways of minimising part count and simplifying the manufacturing process by utilising uniform or standard components. Quite often, the truss members are manufactured as a single block in order to minimise the total part count.

The truss method is well-established practice in the space industry, and carries much aircraft design heritage, although it has evolved to its own specific standards and practices. The truss option was selected for all major constellation satellite systems, due to its simplicity in manufacture and straightforward load path analysis and testing.

Honeycomb

Honeycomb is a well-established material in the aerospace industry. It offers great advantages in

weight savings, thermal properties, load distribution and high specific strength.

Applications include:

- Panels either for component installation or solar arrays.
- Thrust tubes, which act as the main load bearing structure in many satellites. In this case the honeycomb is attached to a combination of longerons and stringers, which forms a frame. The resulting structure is called a monocoque.

Corrugated Sheets

Corrugated sheets are another option for a sandwich structure. In general, the corrugated structure consists of thin isotropic facings, which have negligible flexural rigidity about their own centroidal axes and a highly orthotropic core.

Assumptions made for the cores are:

- Core shear modulus is far greater in the plane longitudinal to the corrugations than transverse to them.
- The core is orthotropic.
- Bending rigidity for the core is negligible in the transverse direction.
- Shear distortions are admissible only in the plane transverse to the corrugations.

Isogrid

Isogrid is a pattern of equilateral triangles integrally machined from a flat surface, with or without material left between the ribs to act as skin. It is isotropic in nature for in-plane loading. Isogrid structures are lightweight and offer high specific strength, bending and buckling strength.

However, isogrid has not been extensively used as a primary structure. Its application is more as a component-mounting platform since the hardpoints available offer a grid platform where components can be arranged.

Such example of isogrid utilisation appears in the HS-601 bus.

The use of isogrid as main structural form was demonstrated in an experimental satellite project called ISOSAT of the Texas University. (8) However ISOSAT is a nanosatellite class therefore no safe assumptions can be made for the isogrid suitability for larger satellites.

Structural Materials

Introduction

In the past decade the choice for the primary structure materials has shifted from almost exclusively metallic structures to full composite utilisation. The metals used were primarily aluminium with steel; titanium or magnesium used at high stress points. Although the practice was well-established and the properties of the materials well known, it had the drawback of high dead weight. However since the numbers of satellites were quite low and the production rate limited the issue of weight was not considered of paramount importance.

With the advent of satellite constellations, though, (where the needs of a production rate reached many dozens), the issue of mass reduction was highlighted. The natural choice was the use of composites. Composite technology had reached an acceptable maturity and therefore it was suited for space qualified applications.

Consequently, the modern designer is blessed with a wide choice of spacecraft materials for any given application, although the criteria of choice are still determined by the operational characteristics and budget. The main considerations focused on are:

- Stiffness (deflection levels)
- Strength (Stress level limit)
- Mass density (mass determination)
- Thermal properties (Expansion, Conductivity)
- Outgassing (material deterioration)
- Corrosion (material deterioration)
- UV-resistance (material deterioration)
- Creep resistance (integrity)
- Availability (choice)
- Legality (choice)
- Cost (budget)
- Development time (timescale)
- Tooling and plant development (budget/timescale)

Metals

Metals were the first materials to be used in the aerospace industry and their use in the satellite manufacture was a natural outcome of this. In terms of engineering, metals have an affordable cost for almost all applications, well established manufacturing and processing methods, known properties and behaviour which, when coupled with their isotropic properties, make stress analysis and sizing calculations a relatively simple task.

Spacecraft metallic structures are developed using either the prototype or the protoflight approach. The minimum design and test factors of safety for metallic structures, excluding fasteners, are specified in the following table.

Table 1 Metal Structures Factors (9)

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0*	1.4	NA or 1.05**
Protoflight	1.4	1.25	NA	1.2

NOTES:

* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.

** Propellant tanks and solid rocket motor cases only.

Composites

Composites are unique materials, combining two or more materials, to utilise the respective advantages of the participating materials. The two main parts are the matrix and the fibre or filament. The fibre is of high strength, high modulus, and low density. The most common are boron, boric (silicon carbide coated boron), and graphite. Boron filaments are manufactured by vapour deposition of boron on a fine tungsten wire. Graphite filaments are made by graphitising tows or bundles of organic filaments. The most common matrix materials are epoxy resin and aluminium.

Although they offer many advantages over the metals, especially low density and high strength, their widespread use is held back by the complex manufacturing procedures, which lead to lengthy and costly development time.

In addition, the anisotropic nature of the material requires special care when load paths are calculated and special methods of attachment have to be utilised (adhesives or fasteners). However this disadvantage can be reduced if a modular construction approach is implemented and advanced manufacturing methods are applied. Furthermore, the overall manufacturing cost increase is a relatively small fraction of the total development cost and the cost increase may be offset

by the launch fee reduction due to smaller mass or the extra payload weight allocation which is freed.

Composite/bonded structures, excluding glass, developed for NASA spaceflight missions shall, as a minimum, use the design and test factors specified in the following table.

Table 2 Composite Structures Factors (9)

Verification Approach	Geometry of Structure	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	Discontinuities	2.0*	1.4	1.05
	Uniform Material	1.4	1.4	1.05
Protoflight	Discontinuities	2.0*	NA	1.2
	Uniform Material	1.5	NA	1.2

NOTE:

Factor applies to concentrated stresses. For non-safety critical applications, this factor may be reduced to 1.4 for prototype structures and 1.5 for protoflight structures.

Material Choice for Structural Components

1. Frame members: The frame consists of struts and tubes, which are generally designed for buckling. Mass reduction can be achieved by using beryllium, boron/epoxy, boron/aluminium, and graphite epoxy. However, due to the manufacturing difficulties of the boron, special diamond based cutting tools, graphite epoxy is more common.
2. Panels: The panels support the subsystem components and enclose the structure. The most common design option is aluminium core honeycomb structure, with either metallic or composite facesheets. Composite facesheets however lack the electric and thermal conductivity of the metals; therefore, metallic inserts are used to compensate for the transfer paths.
3. Thrust cones: The thrust cone is the main load-bearing component of the spacecraft, which utilise one. It is designed for axial compressive loads and bending moments. The main failure

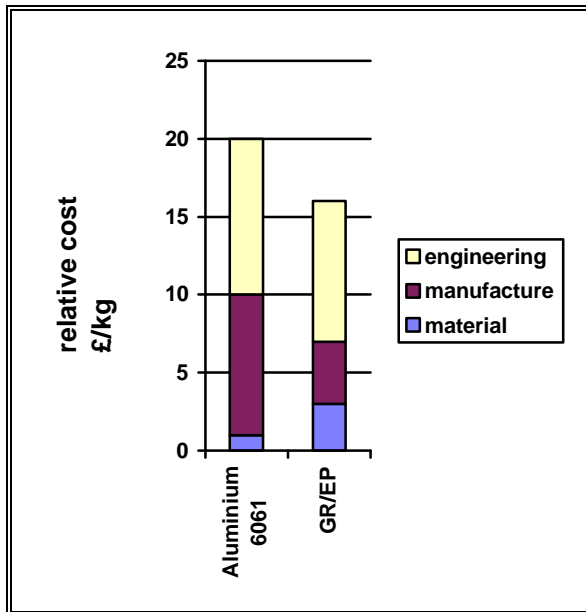
mode is shell buckling. There is a requirement for lightweight high modulus materials, therefore beryllium and advanced composites are used in this section. Thrust cones can be either monocoque, semi-monocoque or sandwich design. The two latter produce more complex designs but are more lightweight.

The use of composite materials in satellite structures was initiated in the design of GEO satellites due to the significant savings in weight growth and therefore the respective reduction in launch fees. However, the utilisation of composite materials for LEO satellites was restricted until recently despite the benefits derived from the weight savings. The reasons were that a series of considerations had to be addressed, most notable being the increased temperatures due to the increase of the power output of the payload, and the limited heat dissipation capability. Weight/volume and power restrictions constitute the utilisation of active heat systems a non-viable or non-attractive solution; therefore, the use of passive systems is almost the standard. EMI shielding available due to the nature of the composites was quite low and the need for increased protection meant that additional metal shielding was needed or the development of special Radiation Hardened electronics resulting in prohibitive cost levels.

The emergence of the LEO constellations however initiated an extensive study at the behaviour of the composites, and efforts were made to enhance their properties. The need for a significant number of satellites allowed the absorption of the cost over a large production run therefore limiting the unit Research /Development cost.

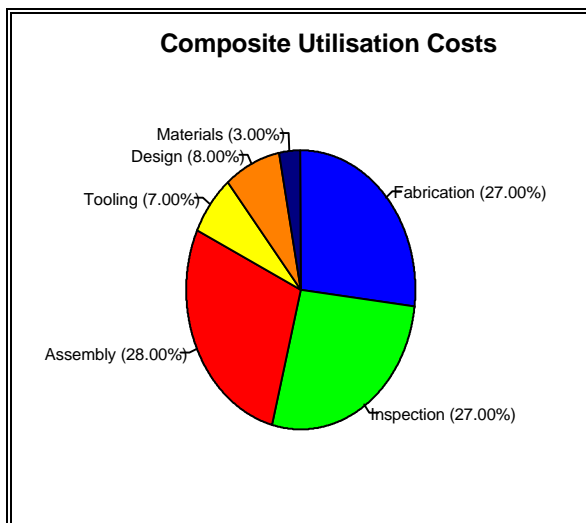
Composite construction offers significant benefits in terms of weight and cost compared to a relative metallic structure. The total weight of the structure is in inverse analogy of the material's stiffness i.e. K1100 < P 120 < M60J < M40J < 6061 Al.

Even with the requirement of EMI shielding the resulted weight penalty does not significantly affect the weight. The procurement cost of the composite materials in terms of (£ / Kg) is significantly higher than the metal alloys utilised in satellite structures. However material procurement cost is comparatively low with respect to the processing and machining costs where the composites have a significant advantage, especially if lean production approaches to manufacture are implemented. The relationship between material procurement cost, manufacturing and engineering cost is shown in the following figure.



Graph 1 Relative Cost of Materials

The overall composite cost breakdown can be shown in the following graph, which shows the part cost as a percentage of the total cost. It is interesting to note that the purchase of the composites as raw material is a very small part of the total cost. However due to the nature of the composite properties, the amount of testing / inspection required is a very significant part of the total cost.



Graph 2 Total Composite Cost

The structure's costs may be controlled further if the following considerations are carefully considered and applied.

- Design for reduction of part count.

One piece modular components, provide the key answer to reduce weight and cost, due to the lack for connectors and the increased toughness associated with a one piece component as no stress concentrations occur which may otherwise have been a point of concern. The limitations in the size of the manufacture of one-piece components lie with the size limit of curing ovens or mould considerations. Other point of concern could be the potential loss of the whole component if catastrophic damage has occurred in a limited region of the component. However the rejection rate can be minimised if careful processing procedures are implemented, furthermore the actual cost savings may constitute a small amount of rejections as acceptable.

Co-cured structures, permit the simultaneous treatment of the components, thus the resulting structure has similar properties throughout. Time and energy savings are possible thus resulting in reduced labour and overhead cost.

- Design for reduction of labour hours.
Batch processing.
Reduction of ply count triax or lightly filled fabrics.

- Design for automation.
Automated process permit an abrupt production output in terms of unit rate and quality as the occurrence

- Design for Integrated Assembly.
The benefits of integrated assembly are mainly size and weight reductions, which result in reduced launch costs. The implemented technologies may require substantial investment and in terms of capital are significantly higher than the conventional methodologies, however this trend is about to change as technology in this field become maturer. An example of integrated assembly is the multifunctional structures, which are reviewed in detail at the chapter of novel technologies.

- Design for low cost tooling approach.
Tooling utilisation covers a substantial percentage of the non-recurring costs during the development of a project. Tooling investment should be judged upon actual amount spent and production output in terms of cost or unit production cost. The manufacture of volume production satellites has enabled the utilisation of manufacturing techniques which were

non-profitable for low unit output projects, especially at the composite material manufacturing and processing level. However this attitude was to be taken a few steps further when it was realised that further cost reductions are needed in order to achieve a high yield return of the investment.

C.O.I utilised the SNAPSAT technology which requires the manufacture of simple flat plates which are simultaneously treated and cured, applies Watergate methods in order to cut the pieces in the desired shape and titanium endfittings to connect the structural elements together. This approach enables the manufacture of the structural components as one piece, thus reducing the need for a large amount of fasteners or end fittings resulting in reduced weight, requires a limited amount of stock resources, notably two different thickness panels and limited tooling in terms of moulds. Iridium utilises a limited part count approach that results in a limited amount of different moulds, thus reducing the overall cost. The simultaneous treatment of the structure during curing provides additional cost savings.

Globalstar and ORBCOMM have decided to solve the problem of low cost tooling and manufacture by opting for aluminium structure. The tooling requirements are metal treatment machines in order to extrude and give the aluminium bars the desired shape, drills, and cutters. The economic potential is based on the relatively better knowledge of metalworking combined with the lower material acquisition costs.

Manufacturing costs may be contained if the option of a dedicated subcontractor is preferred, in some cases the subcontractor is willing to invest on the new technologies that are needed. The benefits of integrating a dedicated partner in the project beside the cost savings are the potential headstart in case of the use of patented and proprietary technology, and the reduced risk involved as each part is concentrating on the field of its expertise. The potential drawbacks of the subcontracting are that the project potential is influenced by the ability of the subcontractor to honour the agreement in terms of schedule and quality. Although clauses for delays or poor quality should be catered for, it is quite possible that any delays could be rather fatal for the viability of the project.

The main cost drivers are:

1. Time: Time parameters include factors like lead time, manufacturing time, processing time and total time. If time is a luxurious commodity, it is likely that the occurring costs will be significant.

In cases where time is the driving parameter it is wiser to opt for proven technologies of low risk and low cost, compared with more modern options, although it is quite possible that a loss in effectiveness and reliability is statistically increased.

2. Mission requirements: Mission requirement is a very broad concept, as it can include the description of the mission scope in both quantitative and qualitative terms. Between those two, there is a fundamental difference, which must be well understood and accepted before the finalisation of an individual mission, or project may commence. To use an example from the satellite industry; the scope of a communications satellite is to deliver and receive signals of a certain frequency range so to permit communication and data exchange. However, the choice of the frequency range, number of channels, quality of reception etc is a different issue. It can be argued that the choice of these parameters will directly influence the design of the satellite systems but still the dilemma is faced once the initial requirements are set. Cost considerations, or technology restrictions will compromise the quality or the capability of the potential design, so it is the task of the project management team to come up with the most effective option available.

3. Process development: It includes all the necessary steps that are needed to be undertaken in order to achieve the final product. Therefore, process development includes both non-recurring and recurring costs.

- Raw material and parts procurement
- Equipment and factory overheads
- Labour costs:
- Risk.
- Testing and Inspection:
- Specific/ Interrelated

Finite Element Analysis

Introduction to Finite Element Analysis (FEA)

Finite element analysis is achieved by dividing the structure under examination into small units called "elements". The element can be given various shapes, although rectangles and triangles are by far the most common. The elements are connected through the "node" points.

The accuracy of the calculations therefore depends heavily on the quality of the modelling of the structure, any assumptions made for boundary conditions, the level of knowledge regarding loading conditions and environment, and of course the number and the kind of elements used to represent the

structure. Although the finer the quality of the elements, the more accurate the calculation gets, this has its toll on computation time, which translates into increase of costs and extension of the projected timetable, for this reason the model should be only as accurate as needed for the task in hand. The finite element analysis involves three major processes.

- Pre-processing
- Solution
- Post-Processing

FEA Model

The bus to be modelled was chosen to be the Loral LS-400, as used for the Globalstar project. Since contact efforts to provide with accurate data failed, the structure was modelled using all available information and extrapolating using appropriate equations in order to solve for unknown properties. The choice of LS-400 was based on the fact that it is a simple structure to model for FEA, therefore reducing the model complexity. Component layout is well documented and available. Finally the same structure was short-listed by NASA in Phase 1 of their Rapid Acquisition Plan, which is a good measure of its engineering merit. (10) The structure of the LS-400 / Globalstar is shown in figure 3.

The satellite's trapezoidal shape, fabricated of a rigid aluminium honeycomb, is designed to conserve volume and facilitate the mounting of multiple satellites within the fairing of a space launch vehicle. Separation of the satellite is achieved by explosive mechanisms, which free the satellite away from a central core dispenser on the launch vehicle. When the satellite is mounted within the fairing of the launch vehicle, the Earth face is oriented outward, and the anti-Earth face is mated to the control, and communications subsystems. The actual Globalstar satellite is strongly based on the Loral LS-400 series and is manufactured under license by Alenia Spazzio of Italy and a series of subcontractors including DASA and Alcatel. At the centre of the satellite a honeycomb platform houses most of the onboard systems while the rest are mounted to the other panels. However for reasons of modularity the Earth facing panel which houses the main communication antenna is manufactured separately and assembled at a later stage.

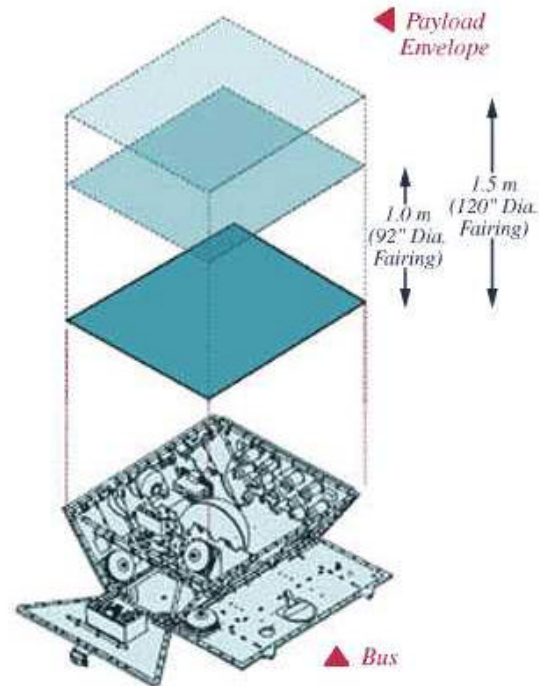


Figure 3 LS-400 Bus Structure

Methodology

Before the actual finite element analysis, a procedure must be followed. The first step is the analysis of the problem, that is the definition of the objectives of the analysis, definition of the environment and forces acting or the boundary conditions and setting the appropriate number of constraints including cost and available hardware and software. The desired output of the analysis was assessed, that is the format and detail of presentation of the results of the analysis. Once the requirements are set, the level of detail for the model can be determined.

All steps and assumptions during the solution process were checked and monitored, clearly documented. This can easily trace way the possible mistakes and corrected, thus saving time and cost. On the other hand though, excessive documentation should also be avoided, especially at the preliminary design stages, as they consume precious time and resources and give an unnecessary level of detail.

The output of the analysis was then checked. Using common sense, it is possible to identify the areas of errors and the reason. A second analysis, using a different technique, will in most cases either verify the validity of the results or give directions to correct the errors. This fact is an inherent flaw of the finite

element methodology; it requires the appropriate input information and instructions in order to process the data and derive the correct solution. The effect of the initial assumptions should be checked. In some cases assumptions have, no detrimental effect on the output accuracy, but the over-simplification of the model could generate a significant percentage of error.

It should be noted that due to the sensitive nature of the space industry it is impossible to obtain accurate values for the required properties. However, it could be possible to derive vital clues by observing the general layout and combine the available data with intuition. E.g., structural mass may be broken down to segments using statistical data depending on the materials utilised and processes applied.

Once the FEA package has computed the output, the presented solution set can be manipulated further, to produce an optimised output through the process of post-processing and optimisation, which enable the designer to observe how the properties of the model change as certain features of the design parameters are varied. Optimisation is quite important as it allows obtaining the most effective solution not only in terms of performance but it can be expanded to a cost saving process as well.

Discussion of the results

Introduction

For the purpose of the analysis a truss based on the LS-400 was designed and a FEA model was made. Also a Flat Plate structure in order to model stress distributions was created. The output for both cases gave useful insight regarding the force load path and the effect of the structural layout in designing an effective load bearing structure.

Truss like structure

The main problem associated with a truss-like structure is the part count. Whether it is of metallic or composite structural members a large numbers of fasteners or end-fittings is required. In this case the option of a composite structure offers significant weight savings both directly, that is the density of composites is lower compared to metals and indirectly that is adhesive bonding can be significantly lighter than fasteners.

In terms of manufacturability, there is a great flexibility. Members can be produced by extrusion, machining, formed out of sheet panels, and moulded.

The main problems associated with the truss structure options are the potential large part count especially in connectors, end fittings, and fasteners, which translates in increased costs due to the increased manufacture times, inspection and testing needed.

Additionally the existence of connectors eventually creates potential weak points in the structure, and locations of probable failure whether being high stress concentrations around fastener holes all adhesive failure attributed to either high stresses or environmental effects.

Figures 4 to 12 show the stress distribution and deflection of the LS-400 structure. It can be shown that the connectors' locations exhibit the highest stress concentrations while the lower frame of the payload and antenna panels are deflected the most.

The problem of reducing part count can be addressed by implementing batch manufacturing like SNAPSAT where large single pieces are manufactured, co-curing of components and moulds. Moulds although it is an initially expensive investment the benefits gained in the long run for a volume production run can offset that expense. In addition to weight savings this approach reduces waste and lead times, making a composite approach comparable to metallic structures therefore reducing project cost considerably. Regarding metallic trusses, practices such as high speed machining can produce large number of components at a minimal time with low tooling costs.

“Flat designs”

Flat designs include honeycomb, corrugated plate and isogrid. Regarding their use in the Small Satellite field, all of their applications are focused primarily in the use of these surfaces as mounting platforms for component installation, although the panels they formed could also act as load bearing components.

Their potential advantages for main structural use are quite attractive. They include issues like cheap manufacturing, lightweight construction, reduced part count and high strength. Additionally in terms of assembly they offer a highly efficient area for component mounting with the benefit of ease of component accessibility.

Their ease of integration with electronics in order to form multifunctional structures provides an additional advantage for their potential application in the satellite manufacturing industry, since it can result to serious reductions in terms of mass and overall size of the satellite, thus offsetting the higher costs of such approach. Integration with the heat management and

control system by the use of internal heat pipes reduces the overall mass of the satellite and the size of the protective enclosure. By careful selection of a sun-synchronous orbit it is possible for appendages to provide adequate shade for the components.

Considerations include issues regarding their structural efficiency at severe load cases such as ignition and payload separation, where there is a high probability of increased stress concentrations. Contrary to the isotropic properties of the conventional truss (especially the metallic ones), honeycomb, corrugations and isogrid structures are

orthotropic therefore additional structural analysis is needed especially in the field of the possibility of wrappage. Furthermore the proximity of the components to the launch vehicle-payload clamp may cause failure if no vibration isolators or dampers are installed.

Summary

The results and conclusions derived from the investigation of the alternative structural designs can be shown on the next table.

TRUSS	SINGLE PLATE/MULTI.	HONEYCOMB
ADVANTAGES	ADVANTAGES	ADVANTAGES
Well established analysis	Offer reduction in weight and size.	Stiffness
Generally ease of manufacture	Offer systems integration.	Thermal stability
Flexibility and shape versatility	Offer high accessibility	Lightweight
Choice of materials	Offer total savings by offsetting investment and launch saving costs.	Accessibility
Choice of manufacturing methods	No special investment in tooling is needed.	Low cost tooling
		Ease of manufacture
DISADVANTAGES	DISADVANTAGES	DISADVANTAGES
High tooling investment due to different parts. Specialised tools may be needed.	Unknown quantity	
May produce large part count	Initial investment high. Require large production run to break even. (depends on method)	Isotropic load distribution requires additional testing
If metallic structure fasteners carry significant dead weight	Not attractive option for time pressing projects	Stiffening may be needed to protect against wrappage
If composite structure endfittings choice and adhesive behaviour are considerations		

CORRUGATION	ISOGRID
ADVANDAGES	ADVANDAGES
Stiffness	Stiffness
Thermal stability	Thermal stability
Lightweight	Lightweight
Accessibility	Grid pattern of loading
DISADVANTAGES	DISADVANTAGES
Isotropic	Isotropic
Stiffening may be needed to protect against wrappage	

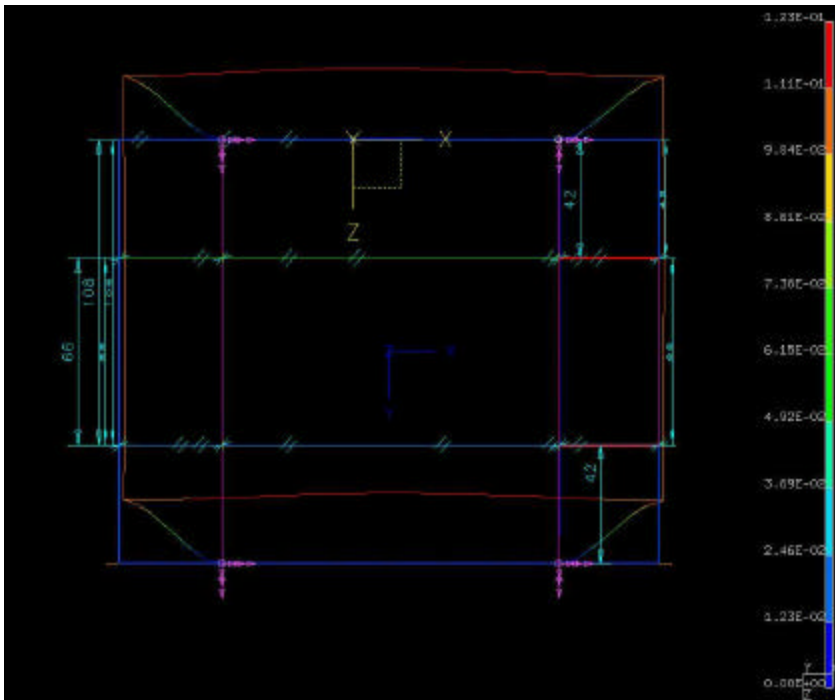


Figure 4 Deflection on structure

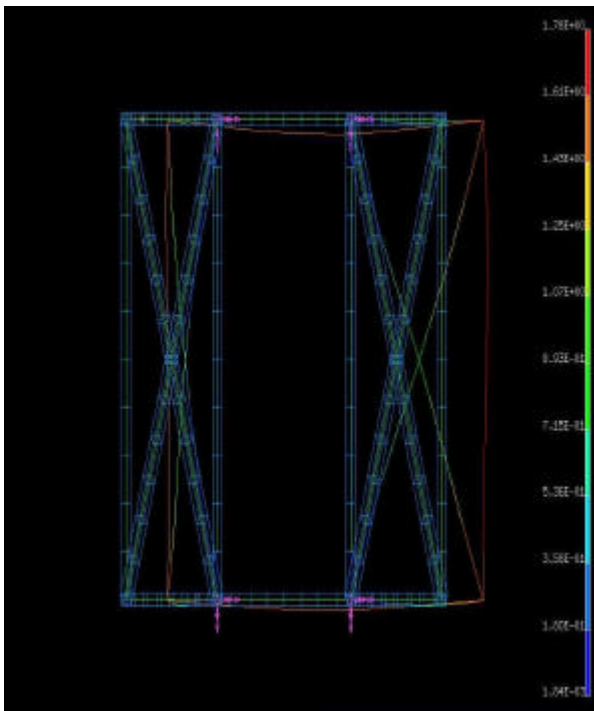


Figure 5 Effects of Diagonals on Structure

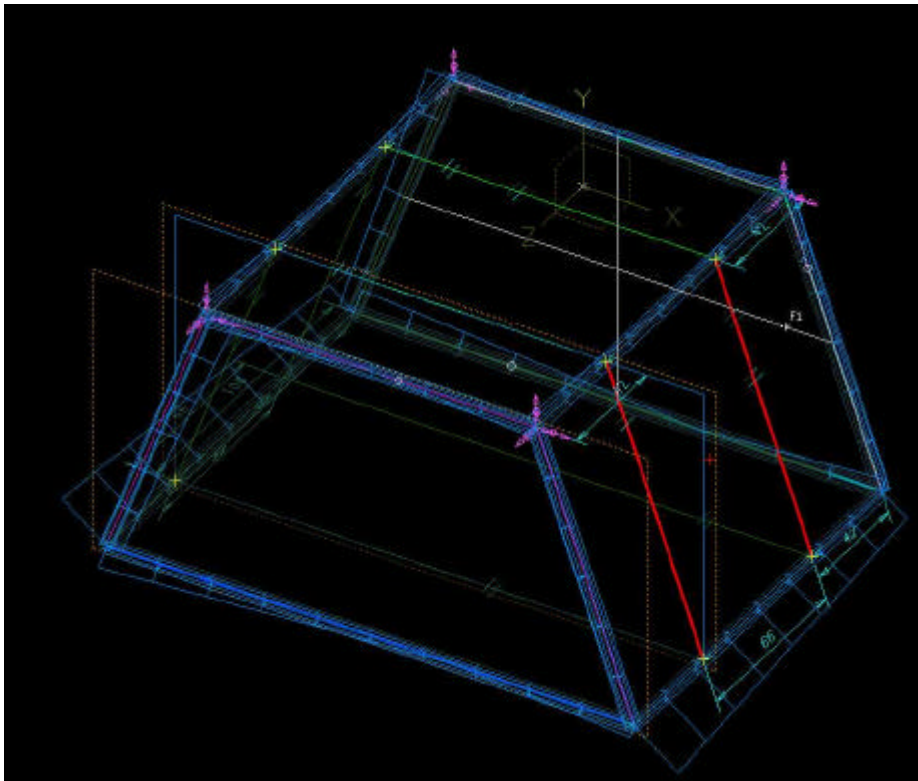


Figure 6 Z/Y Stress

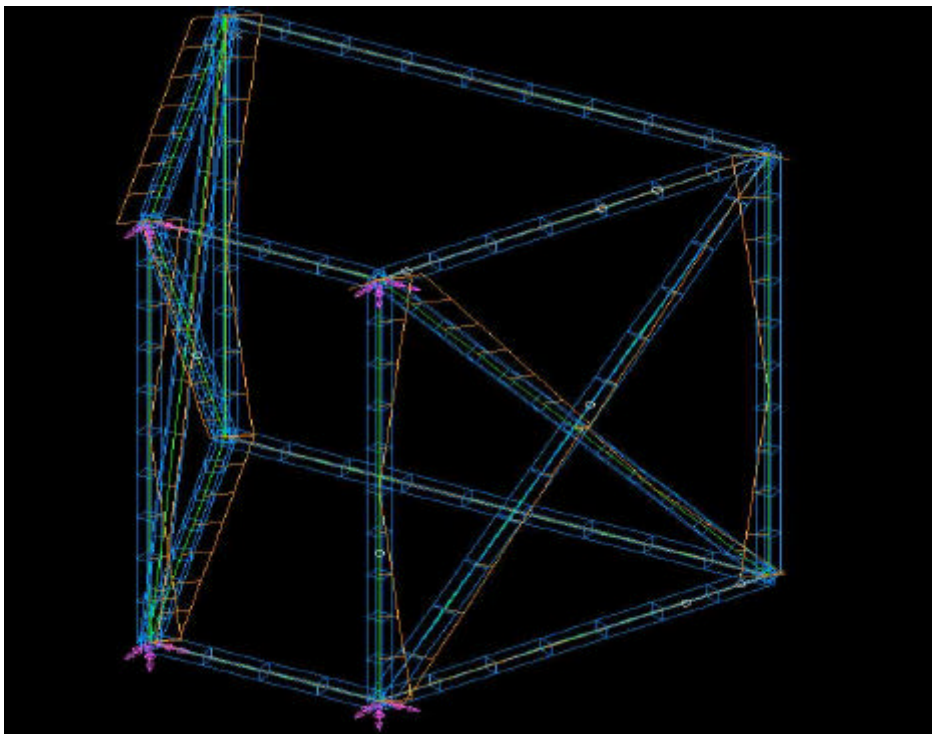


Figure 7 Effect of Diagonals on Z/Y Stress

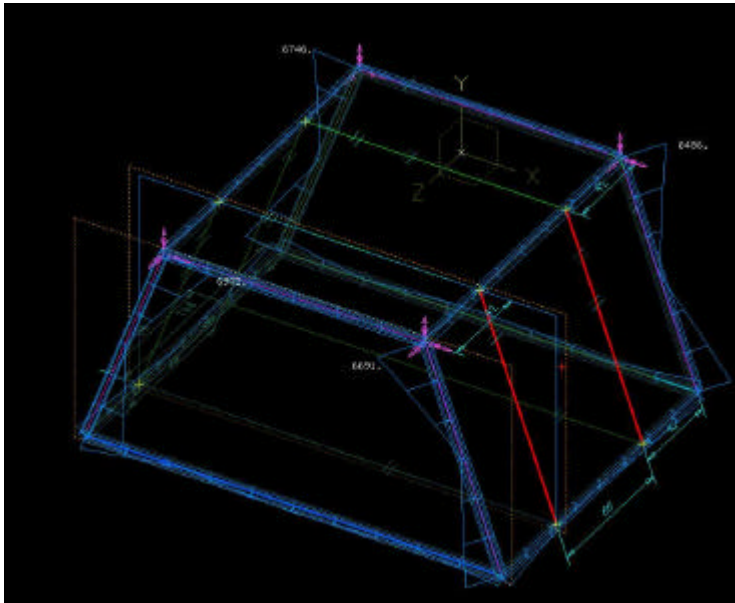


Figure 8 Von Misses Stress Layout

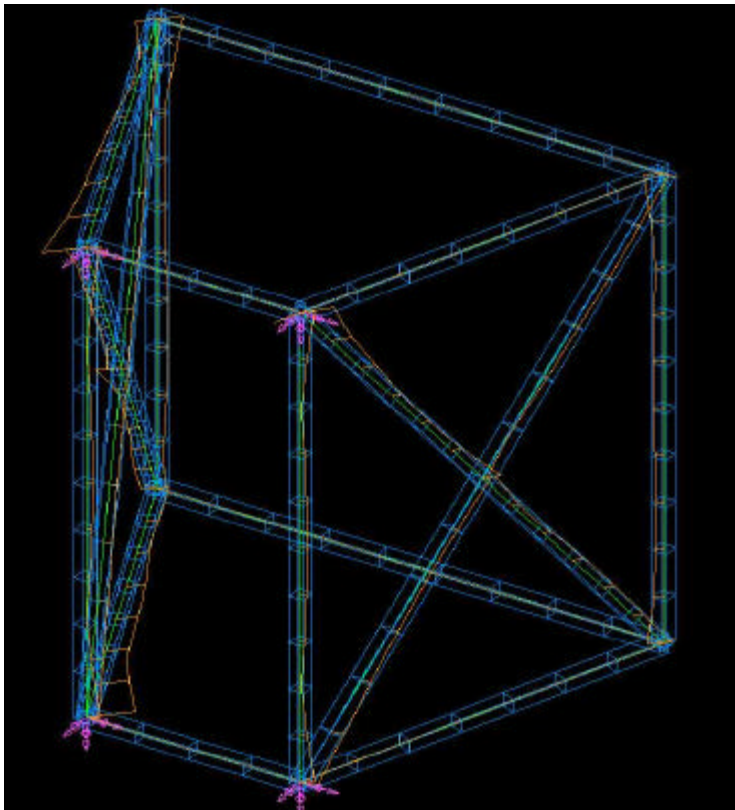


Figure 9 Effect of diagonals on Von Misses Stress

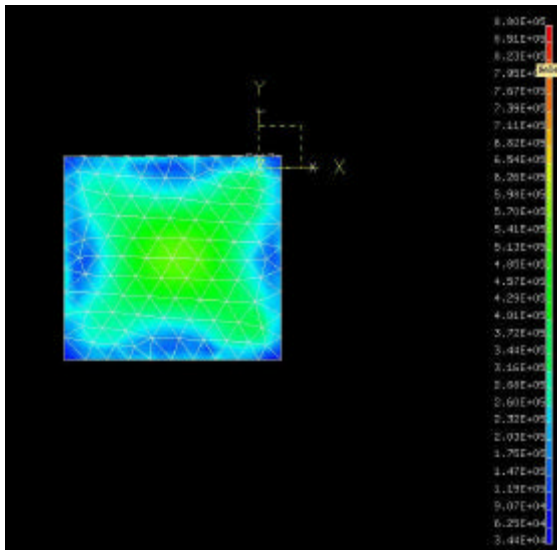


Figure 10 Von Misses Stress Contours on panel

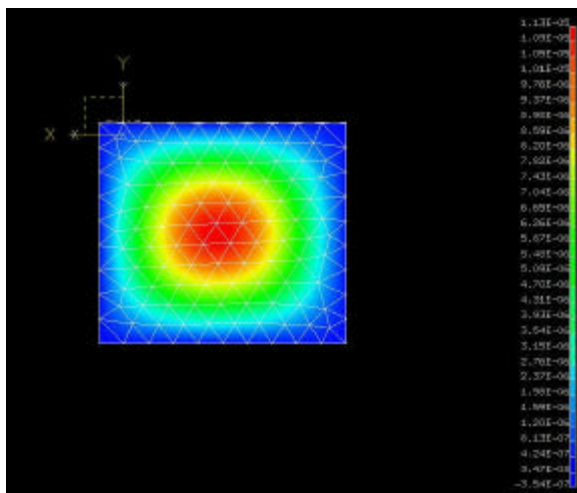


Figure 11 Deflections on panel. Lumped mass located at centre simulates payload.

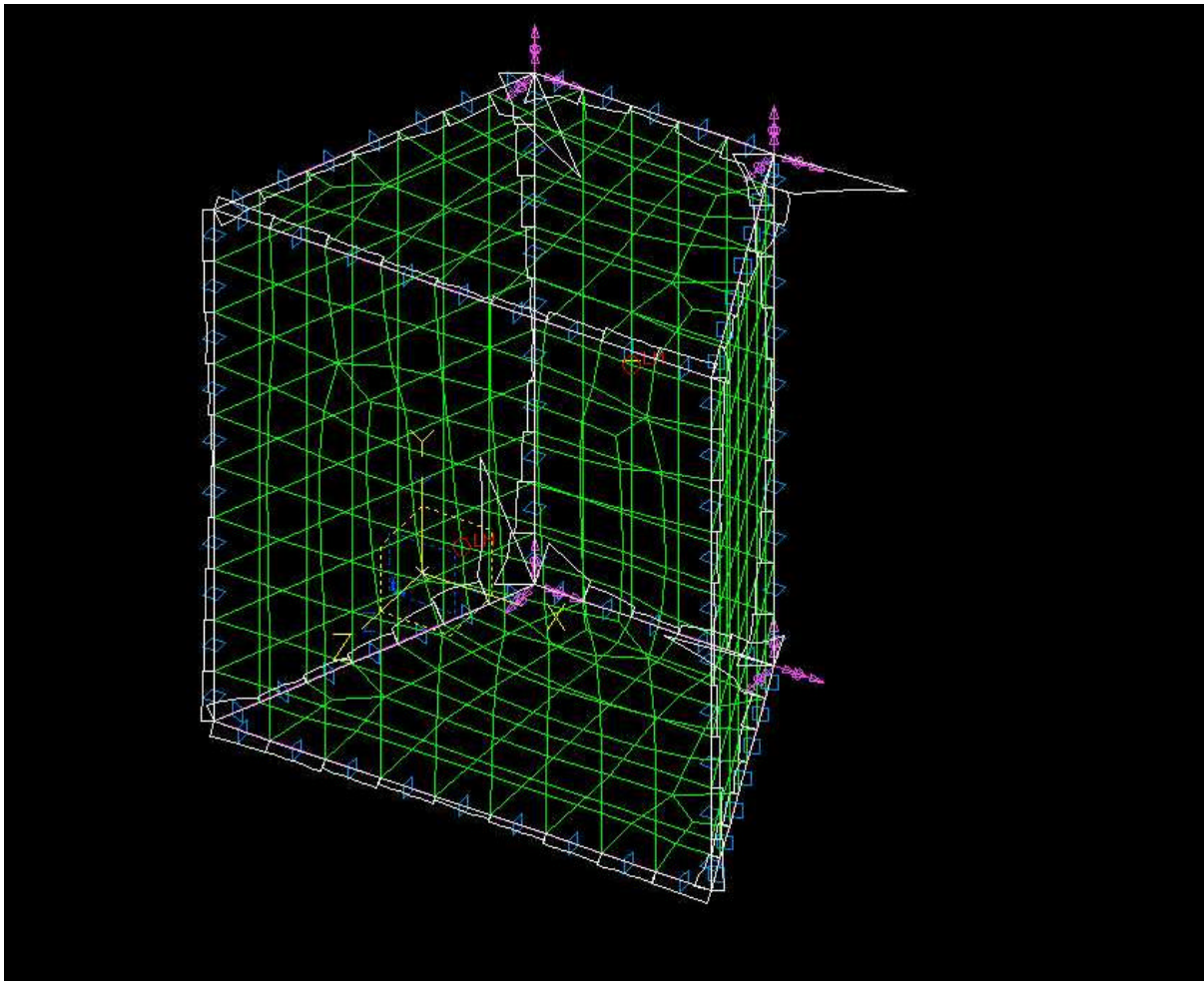


Figure 12 Von Misses on beams showing also the shell mesh. The stress is exaggerated by a factor of 2x in order to show the effect on the end fittings.

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