ANALYSIS AND DESIGN OF A NEW ALTERNATIVE FOR SATELLITE PLATFORMS

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Abstract

The main objective of this paper is to introduce another alternative for satellite structural platforms specially suitable for micro and mini satellites. A brief description of how this approach was conceived, analyzed, tested and optimized is included. Herein are also presented the corresponding sizing formulae and general recommendations for a satisfactory design of this approach.

Nomenclature

B	Membrane stiffness
d	Core hole big diameter
D	Bending stiffness
E	Young modulus
g	Acceleration of gravity
G	Shear modulus
t	Thickness
R	Interaction factor
S	Shear stiffness
V	Shear load by unit of width
Z	Section modulus
υ	Poisson's rate
ρ	Density
σ	Normal stress

Subscripts

a	Adhesive
b	Big holes
B	Intracellular buckling
c	Core
e	Equivalent material
f:	Facing sheet
m	Core material
p	Sandwich plate
s:	Small holes
W	Face wrinkling
Y	Yield

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Introduction

Structural platforms are the commonest spacecraft component used to attach the on board equipment. The main requirements are: clean surface to fix these units, lightweight and high stiffness. Taking into account these requirements the best solution is the sandwich approach, consisting in a layered construction formed by bonding two thin facings to a comparative thick core as shown in Fig. 7. The facings provide practically all of the over-all bending and in plane extensional rigidity to the sandwich. The core serves to position the faces at locations removed from neutral axis, provides virtually all of the transverse shear rigidity of the sandwich, and stabilizes the facings against local buckling. Thus the structural sandwich concept is quite similar to that of a conventional I beam. The core plays a role which is analogous to that of the I beam web while the sandwich facings perform a function very much like that of the I beam flanges. The primary difference between these two types of construction lies in the fact that the transverse deflections are usually significant to the sandwich behavior, whereas for I beams these deflections are only important for the special case of relatively short deep beams.

The sandwich is an attractive structural design concept since, by the proper choice of materials and geometry, constructions having high ratios of stiffness-to-weight can be achieved. Since rigidity is required to prevent structural instability, the sandwich is particularly well suited to applications where the loading conditions are conducive to buckling.

The use of the sandwich construction in aerospace vehicles is certainly not a recent innovation. The British de Havilland Mosquito bomber of the World War II employed the structural sandwich throughout the airframe. In this case, the sandwich was in the form of birch face sheets bonded to a balsa wood core, being the commonest current sandwich construction the honeycomb cells core approach. This paper presents another alternative based in a core that is obtained by a milling process of a thick plate. The design and analysis criteria for the stability of the proposed approach are described to provide the information in a form suitable for easy and rapid use.

General

The job started looking for a sandwich platform easy to fabricate using the available manufacturing technology without paying too much in terms of mass. In order to have a sandwich plate many different core approaches were preliminary analyzed such as honeycomb, web core, single truss, double truss and milled cores with different patterns. Considering the restrictions and after the corresponding trade off studies, a non conventional sandwich configuration was selected, being the main difference between this configuration and the standard honeycomb approach that the core of the sandwich is manufactured by milling a thick plate of a light weight structural material.

Core

During the study phase it was decided to use only circular holes' patterns due to their easy manufacture, low cost, more stable modes of failure and reasonable design considerations. From these alternatives, taking into account the core density, the grade of anisotropy, the corresponding cost and the characteristics of the eventual inserts, the Fig. 1 option was selected to be analyzed and qualified.

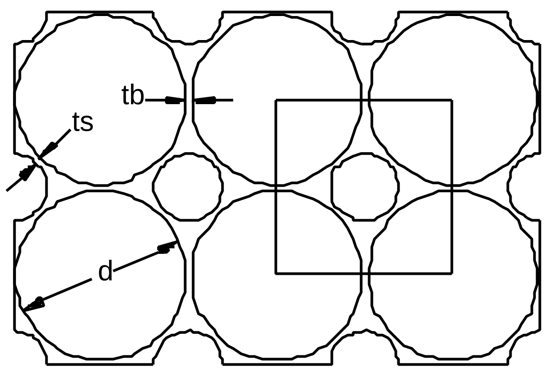


Fig. 1: Selected Pattern

Facings and Bonding

Another difference with the standard solution is that one of these facings can be obtained during the core milling process, avoiding the adhesive and transforming, as it is explained herein, some classical failure modes that appear in the standard approach in non credible, and tough each cell can have only the required thickness instead of a uniform facing sheet thickness, with the corresponding mass saving.

Modes of Failure

Introduction

Standard sandwich constructions use to be checked for two possible modes of instability failure: general instability failure where the sandwich fails with the core and facings acting together, and local instability failure. These structural instabilities of a sandwich can manifest itself in a number of different modes. During the study phase the instability failure modes of the standard sandwich approach with the addition of Facing Failure and Core Unglue were considered. The analyzed possibilities are described bellow:

Transverse Shear Failure
Local Crushing of Core
Shear Crimping
Face Wrinkling due to Core Compression
Face Wrinkling due to Adhesive Bond Failure
Intracellular Buckling
Core Unglue
Facing Failure
General Buckling

The transverse shear failure, the local crushing of core, shear crimping and face wrinkling by core compression represent non credible modes of failure due to the high core strength and stiffness as it was verified by the corresponding analyses and tests.

Design Equations

The Critical Stresses formulae for the remainder modes of failure are described in the following points. These expressions have been obtained from the analytical ones and adjusted according to test results.

Face Wrinkling

This is a localized mode of instability which manifest itself in the form of short wavelengths in the facings, it is not confined to individual cells and in the proposed solution involves the tensile rupture of the core to facing bond. This mode of failure is analogous to a plate on an elastic foundation. The elastic foundation consists in the spring rate of the core material perpendicular to the faces, with the plate being the faces themselves. In our construction it buckles only outwards due to the relative strengths of core in compression and adhesive in flatwise tension. Fig. 2 shows this failure mode.

This mode of failure is generally non critical due to the high value of the core Young's Modulus. For standard milled core geometry and conventional loads, usually this critical value is greater than yield. The maximum allowable uniaxial compressive face stress based on face wrinkling can be computed by the following formula:

$$\sigma W = 0.25 \left(Ec\ tf / (Ef\ tc) \right)^{0.5} * Ef$$

When the facings are subjected to biaxial compression, it is recommended that one use the interaction formula:

$$Rx^3 + Ry = 1$$

where Ri is the applied compressive loading in subscript direction divided by the critical compressive loading (when acting alone) in subscript direction. The y direction corresponds to the direction of maximum compression. For cases involving shearing stresses which are coplanar with the facings, it is recommended that the principal stresses first be computed and that these values then be used in the above interaction equation. Whenever one of the stresses is tensile and the behavior is elastic, the analysis should be based on the assumption that the compressive principal stress is acting alone

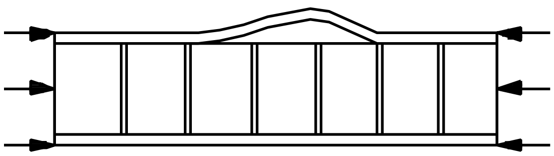


Fig. 2: Face Wrinkling - Adhesive Bond Failure

Intercellular Buckling

It is a localized mode of instability which occurs only in the regions directly above core cells, the facing buckles in plate-like fashion with the cells walls acting as edge supports, occurs with very thin facings and large core cells. The maximum allowable uniaxial compressive face stress based on monocell buckling is from test results:

$$\sigma_B = K_B \, Ef \, (tf / d)^2 / (1-\upsilon^2)$$

The factor K_B varies from 4 for facing sheets bonded to 4.4 for facings obtained during the milling process, the critical stress can be easily increased by a chamfer (radius) as presented in Fig 8 II and 9 II. It is necessary to remark that in some cases it seems to be the critical, but is not a catastrophic mode of failure, since if one cell fails the platform strength and stiffness will not change significantly as it was observed during the corresponding tests.

When the facings are subjected to biaxial compression, the same criteria of Face Wrinkling apply and the following interaction formula can be used:

$$Rx + Ry = 1$$

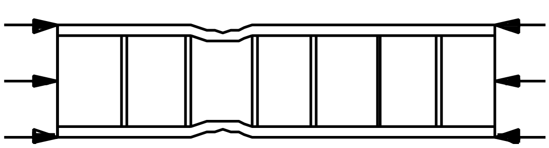


Fig. 3: Intracellular Buckling

Core Unglue

Bending generates shear stresses which cause that the faces tend to slide with respect to core. Occurs when the shear stress at facing-core interface is greater than the adhesive allowable value. Then the critical stress in this mode is the allowable shear stress of the adhesive. In order to preclude this type of failure the shear stresses at the adhesive plane should be smaller than the value described by the following expression:

$$\tau = \tau a$$

When the Core Unglue is the critical mode of failure, the sandwich strength can be easily increased by finishing the critical cells border with a small chamfer as shown in Fig 9 II.

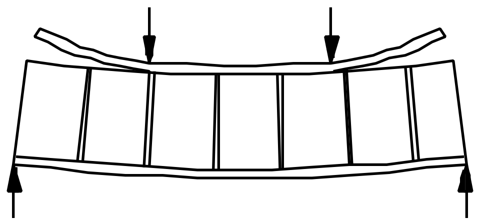


Fig. 4: Core Unglue

Facing Failure

Initial failure may occur in either compression or tension face. Caused by insufficient panel thickness, facing thickness or facing strength.

This mode of failure, depending on the geometry, uses to be the critical one. It appears when the Von Misses Stresses acting in the facing or the core reach the yield value of the corresponding material. The following equation shows the relationship used in this failure mode:

$$\sigma f = \sigma Yield$$

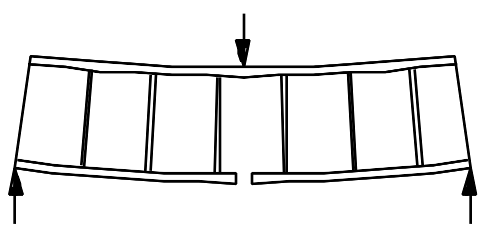


Fig. 5: Facing Failure

General Buckling

Caused by insufficient panel thickness or insufficient core shear rigidity. The critical stresses can be computed using the standard formulation[1, 15] for flat sheets in compression, shear, bending and under combined systems. They have to be analyzed case by case taking into account the particular load case and the corresponding boundary conditions.

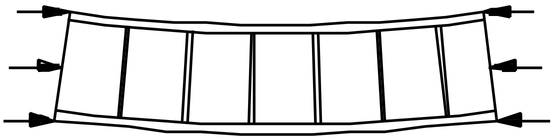


Fig. 6: General Buckling

Sandwich Characteristics

Core

The following core formulae have been developed for the selected pattern showed in Fig. 1 dashed lines.

Core Density

This value can be computed as the pattern area minus the milled area multiplied by the actual core material density and divided by the pattern area. The resulting value is the following:

$$\rho_c = \rho_m \,(1-0.79(d^2+(1.41(d+tb)-d-2\,ts)^2\,)/(d+tb)^2)$$

The minimum value of ρ_c is 8 % of ρ_m when tb and ts are equal to zero. The practical values are between 10 and 13%.

Core Young Modulus

It can be obtained from the Young's Modulus corresponding to the material used in the core and ultiplying it by the core density and dividing it by the density of the core material.

$$Ec = Em\, \rho_c / \rho_m$$

Sandwich Model

Stiffness

The actual sandwich can be transformed into an equivalent isotropic material that is very suitable to simplify the analyses. Herein are presented the relationships that allow the transformation. They were determined considering the same material for core and facing sheets (Ef = Em = Ep) and the same thickness for both facings ($tf_1 = tf_2 = tf$). The equivalent characteristics of the sandwich plate were obtained by identifying its membrane, bending and shear stiffness - for the minimum resistance transversal section - to those of an isotropic plate, see Tables 1 and 2.

$Bp = Ep\,(2\,tf + tc\,(1 - d / (d+tb)))\,/\,(1-\nu^2\,)$
$Dp = Ep\,((tc + 2\,tf)^3 - tc^3\,d / (d+tb))\,/\,(12(1-\nu^2\,))$

Sp Gp tc tb / (d+tb)

Table 1: Sandwich Stiffness by Unit of Width

$Be = Ee\,te / (1-\nu^2\,)$
$De = Ee\,te^3\,/\,(12\,(1-\nu^2\,))$
$Se = Ge\,te$

Table 2: Isotropic Plate Stiffness by Unit of Width

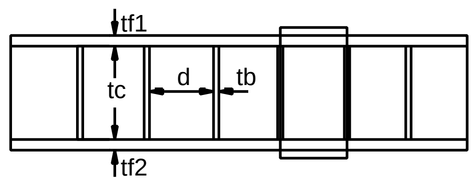


Fig. 7: Minimum Resistance Transversal Section

Test results showed good approximation between the behavior of the sandwich and the minimum resistance transversal section model.

Equivalent Isotropic Material

Making the membrane, bending and shear stiffness of the sandwich equal to the corresponding value of the isotropic plate the equivalent isotropic material properties were obtained. With these new equations the Thickness, the Young Modulus, and the Shear Modulus of the equivalent isotropic material were determined. These relationships can be used for either static or dynamic computations instead of the sandwich ones in order to simplify the mathematical model computations:

Thickness [te]

$$tc(((1 + 2\,tf/tc)^3 - d/(d+tb))/(2\,tf/tc + 1 - d/(d+tb)))^{0.5}$$

Young Modulus [Ee]

$$\frac{Ep\,(\,2\,tf/tc + (1 - d / (d+tb))}{(((1+2tf/tc)^3 - d/(d+tb))\,/\,(2tf/tc+1-d/(d+tb)))^{0.5}}$$

Shear Modulus

$$Ge = Gp\,tc\,tb / te\,(d+tb)$$

Poisson's Rate

$$\upsilon e = \upsilon p$$

For sandwiches with different facing thicknesses the same procedure presented herein can be followed to identify the equivalent isotropic material relationships.

Stress Recovery

After using the equivalent material to compute the equivalent stresses it is necessary to recover the actual working stresses. The recovery formula is showed below and comes out making the moment as a function of the stress for the isotropic material equal to the moment as a function of the stress for the sandwich construction. The actual normal stress can then be found using:

$$\sigma_p = \sigma_e \, Ze / Zp$$

Where the section modulus by unit of width are:

$$Z_p = ((tc + 2\,tf)^3 - tc^3\ d / (d+tb)) / (12\,(tc/2 + tf))$$

$$Z_e = te^2 / 6$$

Sizing Process

In order to know the safe dimensions of the analyzed platform the following procedure can be followed:

1 - Propose the sandwich platform dimensions.

2 - Obtain the corresponding equivalent isotropic material parameters

3 - Make the model of the platform considering that is made of the equivalent material.

4 - The equivalent stresses then can be computed assuming the isotropic equivalent material approach. This model can be solved by the classical analytical expressions or a Finite Element Model can be used instead.

5 - Recover the actual working stresses from the equivalent ones.

6 - Compute the corresponding Margin of Safety for each Mode of Failure.

7 - The process finishes when all Margins of safety are greater than zero.

When different materials are involved the method consisting in the transformation of all sandwich layers (facings and core) into the same material using the corresponding Young Modulus method is very suitable, in these cases the procedure can be summarized as follows:

1 - Propose the sandwich platform dimensions.

2 - Transform the actual sandwich - made of different materials - into o new one with all layers made of the same material. using the Young Modulus method.[1]

3 - Determine the stiffness for this same material sandwich.

4 - Obtain equivalent isotropic material relationships and the corresponding values.

5 - Make the model of the platform considering that is made of the equivalent material.

6 - The equivalent stresses then can be computed assuming the isotropic equivalent material approach.

7 - Recover the working stresses for the same material sandwich.

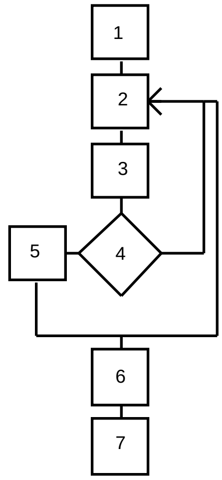
8 - Recover the stresses for the actual sandwich plate using the Young Modulus Method.

9 - Compute the corresponding Margin of Safety for each Mode of Failure.

10 - The process finishes when all Margins of safety are greater than zero.

Optimization procedure

Taking into account that the facing sheets, core plates and milling cutters came in dimensional steps and considering that each core and facing material has different properties from the other materials and there is no law to relate the material properties in between, a discrete optimization process was adopted. This process consists in the screening of all reasonable combinations of tc, tf, Ef, σy, d, etc., (tc and ts are fixed to the minimum manufacturing values), computing the stresses for the proposed geometry using the equivalent isotropic plate model, recovering the stresses, comparing them with the critical stresses, rejecting the combinations where the actual stresses are greater than the critical ones or do not satisfy the frequency requirements, and when all feasible combinations have been computed sort them by mass and analyze the file containing this information. The following flow diagram was included herein in order to clarify this process:



Diag. 1: Optimization Procedure

The meaning of each block of the diagram is presented below:

1 - Loading of the known values in the computer program (e.g. Materials Properties, tb, ts, minimum frequency requirements, etc.)

2 - Loop headers of each design variable (e.g. Initial db, final db, and the corresponding step).

3 - Dependent Variables determination (e.g. computation of actual working stresses, margins of safety, etc.)

4 - Determination of the feasibility of the solution (e.g. computed frequency lower than required, negative margin of safety, etc.). Loop until last combination.

5 - Storage of the feasible combination and mass determination of this solution. Loop until last combination.

6 - When all combinations were computed a sort by mass process is performed with the feasible ones creating the criteria file.

7 - This criteria file containing the first tenths of alternatives has to be examined by the designer in order to choose the most satisfactory option so as to take into account the aspects that couldn't be included in the software and that are generally discovered when the analyses of the criteria file is performed (the satisfactory option might not be the lightest, e.g. If the second one is a few grams heavier but the Margin of safety is 2 times greater, the second one might be the most eligible).

Design Considerations

The following considerations should be taken into account in the design of a satellite platform based in the proposed approach.

Milled Facing

As it was expressed herein one of the facings can be obtained during the core milling (Fig 8), this alternative reduces the quantity and the criticality of the failure modes (only Intracellular Buckling, Facing Failure and General Buckling remain). In this case it is convenient to allocate the machined facing where the compression is higher. In this configuration it is also possible to easily get different facing thicknesses in each hole (Fig 8 I) in order to have only the necessary, resulting in an additional mass saving that has to be added to the saved adhesive mass.

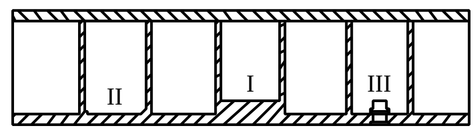


Fig. 8: Milled Facing

Facing thickness

Satellite platforms generally have only one facing sheet working at maximum compressive stresses (specially when they are located normal to the launcher thrust axis). In those cases only the thickness of the critical cells, that are usually very few, can be increased (Fig 8 I and 9 I) avoiding the use of a uniform facing thickness sized for a few cells.

The borders to increase the Face Wrinkling, Intracellular Buckling and Core Unglue (Fig. 9 II) do not increase the platform total mass, because they only represent a small extra weight that is well compensated by the mass saved in the facing sheets.

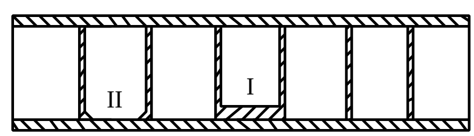


Fig. 9: Cells Details

Inserts

Whenever possible, in order to save mass, it is a good practice to allocate the interface holes on the center of the smaller diameter cells. In these places the unit can be fixed to the platform core by means of a helicoil, weighting this kind of "inserts" from 1 to 3 grams each depending on each particular design. The centers of the interface holes do not need to be exactly imposed by the pattern, because it is possible to have some variation around these points. To maximize this insert option at the beginning of the project it is very convenient to suggest that the units interface footprints be defined in core steps (d+tb). Also the structural element fixation points should use these places to minimize the inserts' mass. It is necessary to remark that these inserts are made directly in the core with the corresponding increase in their strength and they are almost ready after core manufacturing.

Nut rivetless plates (Deutsch type) can be used as other lightweight inserts (Fig 8 III and 10) which are easy to install having a low cost and delivery time. Depending on the loads these nut plates can either be mounted directly on the bonded facing cell or require a configuration as shown in Fig 8 I or 9 I. They can also be allocated in standard or flush mounting approach. Fig. 10 presents a blind hole nut plate and a bonded insert nut plate mounting designs.

Many other "inserts" can also be used according to the specific design constrains.

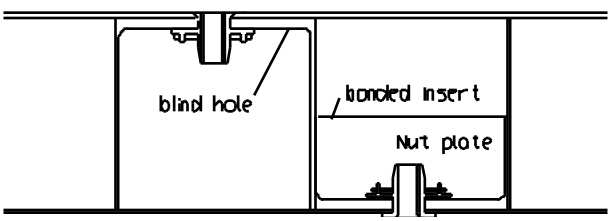


Fig. 10: Nut Plate Inserts Details

Off Gassing

The off gassing is obtained by milling diagonal slots on one side of the core, These slots have been checked to have no relevant influence in the behavior of the panel.

Manufacturing Considerations

The numerical control machines with the corresponding CAD/CAM system are the most suitable to manufacture this kind of sandwich platforms.

The big core holes can be manufactured only in two milling times (for holes smaller than 35 mm diameter).

The distance between the big holes (tb), to avoid excessive fixation points specially when the platform edge is greater than 50 cm, has a practical manufacturing limit of 0.5 mm. For ts, the small hole distance, 0,35 mm or thicker are recommended. These two values can be reduced by chemical milling up to 60%, but increasing obviously the manufacturing cost and delivery time.

The time to machine these kinds of cores lasts approximately from 0.5 to 1.5 hour for each liter of core volume.

Miscellaneous

To compute the total mass of the sandwich it has to be underlined that the total platform weight is not only obtained from the facings and core weight, but also necessary to compute the mass of these elements plus inserts with the corresponding potting, the non standard inserts, the edge closures, the adhesive weight, the doublers (mechanical and thermal), heat pipes, etc. As a rule of thumb the mass of this platform is competitive to the classical one when the platform surface is lower than 0.3 m^2.

It is easy to make panel edge closures, has more stable failure modes, excellent thermal conductivity avoiding doublers or heat pipes, etc. and does not need any manufacturing technology development, good results can be obtained with platform thickness lower than the used in the standard honeycomb approach.

Experiment Description

In order to know the behavior of this sandwich concept an experiment following the corresponding statistical rules was designed. This experiment that combines different materials and thicknesses of sandwiches and cores, was analyzed using regression analysis and factorial design. Factorial designs are widely used in experiments involving several factors where it is necessary to study the joint effect of the factors on a response. The 2^4 design was chosen in order to determine the influence of some variables and their interactions to validate the analytical equations used to predict the failure stresses. The variables used in the design were, as it was mentioned, the thicknesses and materials of core and facings, each one having two levels, then the complete replicate of such a design requires 16 observations or test specimens. Because there are only two levels for each factor, we assume that the response is approximately linear over the range of the factor levels chosen.

The regression analysis methods are frequently used either to analyze data from designed or unplanned experiments. Generally, the analysis of variance in a designed experiment helps to identify which factors are important, and regression is used to built a quantitative model relating the important factors to the response. The 2^4 factorial design was complemented with some other specimens, then the regression analysis was planned in order to have a cross check.

Mathematical models (equivalent and finite elements) were constructed to predict the acting stresses and the corresponding failure modes. The computed critical stresses were correlated with the test results and then critical stresses formulation was adapted. Unfortunately at the time of writing this paper the statistical analysis could not be fully finished, but the information presented herein is well correlated with the studied test results and the corresponding mathematical models. The following figure shows the core corresponding to the four points flexural test specimen where d is equal to 25 mm and tb is 0.5 mm.

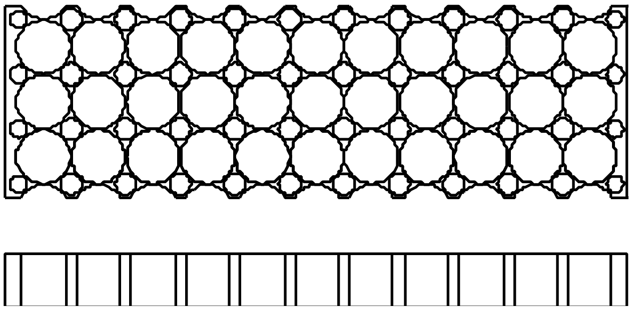


Fig. 11: Test Specimen Core

Conclusions

This job was not focused on developing a high performance sandwich platform to replace the classical one, the aim of this job was nevertheless to have a platform easy to manufacture at the lowest feasible cost. In order to decide the use this approach instead of the classical one, we strongly suggest to make a comparative analysis between both approaches during the study phase. The final result shall depend on the environment where the project has to be developed because the pondered influence of the characteristics of this approach depends on each particular design and has to be analyzed on a case by case basis. To choose between this approach and another one, specially the classical honeycomb one, at least the following items should be analyzed:

- Available Manufacturing Technology
- Schedule Constrains (delivery time)
- Thermal Conductivity Requirements
- Concentrated and Impact loads
- Available Budget
- Hard Points Density
- Necessity of Local Reinforcements
- Handling and Transporting Criticality
- Necessity of Panel Edge Closures
- Quality Assurance Requirements
- Available Volume (lower thicknesses)
- Allocated Structural Mass Budget

Acknowledgments

The authors would like to acknowledge herewith the support and cooperation of number of organizations and individuals, in particular R. Diaz from the UTN Secretary of Science and Technology, J. C. Mesina Head of FRBA Test of Materials Laboratory and the CIMHER group Head.

Glossary

ASI	Italian Space Agency
CoNAE	Argentine Space Agency
NASA	National Aeronautics and Space Administration
SAC-B	CoNAE, NASA satellite
UTN	Universidad Tecnológica Nacional
FRH	Facultad Regional Haedo
FRBA	Facultad Regional Buenos Aires
CIMHER	Centro de Investigaciones - INTI - Argentina

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