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Optimization of Multifunctional Battery Structures for Mars

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***Abstract*—**Multifunctional structures are a potentially disruptive technology that allows for significant mass savings on spacecraft. The specific concept addressed herein is that of a multifunctional power structure. In this paper, a parametric optimisation of the design of such a structure that uses commercially available battery cells is presented. Using numerical modelling, it was found that there exists several trade-offs aboutthe conflict between the capacity of the panel and its mechanical properties. It was found that there is no universal optimal location for the cells. Placing them close to the mechanical interfaces increases loading in the mechanically weak cells whereas placing them at the centre of the panel increases the stress inthe panel and reduces the stiffness of the structure.

***Keywords*—**Design Optimization, Multifunctional Structures, Power Storage.

I. Introduction

MARS rovers benefit from improved efficiency and cost when they have lower mass. Multifunctional structures (MFS) are a technology attracting increasing interest in the last decade as a method to provide lighter weight missions [1]. A multifunctional structure is one that incorporates additional spacecraft functions in addition to its mechanical functions. This reduces the number of discrete components inside the rover bus, removing the need for tertiary parasitic structures to mount these components into position. There is also a volume saving as less space is needed inside the rover bus.

The concept of a multifunctional power structure (MFPS) has been developed by Roberts and Aglietti [2, 3]. This is a multifunctional structure that contains part of the electrical power system. The specific application considered is shown in Fig. 1: a sandwich panel with battery cells embedded into the core.

The application makes use of commercially available cells. These are preferred to the traditional custom built battery pack because they are superior in terms of quality, capability and cost. To manufacture custom components in low numbers requires the use of manual labour as it is not economic to automatic a process so infrequently used. This creates an issue with quality control which may require either compromises to the design or the manufacture of additional parts to meet the desire performance. More consistent productivity can be achieved through mass production.

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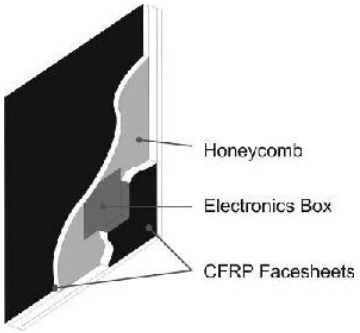

Fig. 1 The multifunctional power structure concept

Purchasing off the shelf components removes the need of the manufacturer to develop or find a suitable source of custom battery manufacturing, reducing complexity.Finally, commercial off the shelf (COTS) cells are significantly cheaper due to their high production numbers. Additionally, faulty cells can be easily replaced with the lead time being that of shipping only.

The objective of this paper is to present an optimisation of the concept. The goal of the optimisation is to determine how a set of prescribed parameters affect the structural performance of an MFPS and from there make recommendations on the interaction between power storage and mechanical properties. The optimisation was carried out using a finite element model.

II. Parameters

The large body of work that has already been carried out into the optimisation of composite sandwich panels has resulted in a preference for thick core and thin facesheets as the preferred compromise between structural performance and panel mass. As there is clearly little benefit is redoing this work, the optimisation of the MFPS will focus on the influence of the battery cells. The following are the parameters that define how the cells are incorporated onto the panel:

- Cell Number

The greater the number of cells that are included in a panel, the greater the specific energy of the panel.

- Cell Location

The location of the cells in the panel. Locating the cells near the edges of the panel is preferred as this will reduce any effects on the vibration properties of the panel. This

requirement must be balanced against the attachment requirements of the panel which will likely take up space along the edges of the panel. The corners of the panel are also excluded as these areas must be left free for the bracket mounting inserts. It is preferred for manufacturing that the cells be grouped together.

- Cell Stack Height

The number of cells stacked vertically. The depth determines how many cells can be included in the structure for a given area. Stacking the cells such concentrates the extra mass added to the panel, increasing panel loading. The benefit is that the required number of cells can be reached if the area available is too limited.

- Cell Orientation

How the cell is orientated in the panel.

III. Design of Panel

The panel is comprised of carbon fibre reinforced polymer (CFRP) facesheets and an aluminium honeycomb core. As the function of this study is not to optimise the materials, typical materials and properties were selected, which are detailed below. The materials used were selected for their availability rather than their mechanical properties, as the focus is on optimisation of the battery configurationrather than design of an ideal structural panel. An insert representing the mounting location of the panel is included at each corner. The thickness of the core and the inserts is determined by the stack height of the battery cells.

A. Facesheets

The facesheets are made of CFRP. The sheet is a commercially available product made of T300 fibres and epoxy resin in a 0-90 lay-up. The sheet is 300 mm by 210 mm by 0.4 mm thick. The material properties are thus: In Plane Young's Modulus = 111 GPa, Poisson's Ratio = 0.35, In Plane Shear Modulus = 41 GPa. The density is 2063 kg/m^3.

B. Core

The core is a 5052 aluminium honeycomb. The cell size is 3.175 mm and the wall thickness is 0.0508 mm. The compressive modulus is 2.413 GPa and the shear moduli are 931 MPa and 372 MPa. The density is 130 kg/m^3.

C. Inserts

The inserts are made of alpha-beta titanium and are 12 mm by 12 mm. The elastic modulus is 114 GPa and the Poisson's Ratio is 0.322. The density is 4540 kg/m^3. Titanium is preferred over aluminium due to its co-efficient of thermal expansion matching better with the CFRP facesheets.

D. Battery

The battery cells selected are Varta LPP503759 DL. They are 60 mm by 37.5 mm by 5.2 mm thick. Roberts and Aglietti [3] have shown that the shear modulus of the cells is non-linear. To account for the worst case scenario, the lowest value in the range, 24 MPa, is used. [3] also shows that the Poisson's Ration has little effect on the cells performance as a core material. The cells have a density of 1980 kg/m^3.

This commercially available cell was selected for its superior properties in addition to having the highest specific capacity commercially available. As a solid state chemistry, there are no liquid parts and the battery casing is not a pressurised container. This lowers cell mass and removes the risk of leakage from the cell. The cell is prismatic in shape making it much easier to incorporate into the rectangular geometry of the sandwich panel.

IV. Cell Layouts

The range of potential cell layouts is refined by definition of the ranges of the parameters previously discussed. The two possible orientations of the cells are shown in

Fig. 2. The B orientation is preferred as it allows for more cells to be placed along a given panel edge length and allows for easier access to the cell contacts.

Fig. 2 also illustrates that the cells should be placed at the edges of the panel to allow for better electrical access.

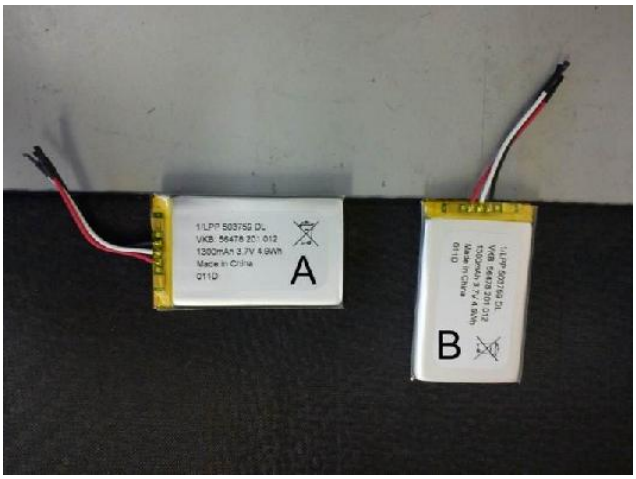

Fig. 2 The possible cell orientations

Fig. 3 shows the range of considered stack heights. Stacks which require honeycomb between cells or cells between honeycomb are not considered due to the complexity of the manufacturing. Heights greater than 4 cells were not considered as this would require a core thickness of greater than 20 mm. This thickness of core is rare in small spacecraft applications. Fig. 4shows the range of possible stack locations. The cell location is varied with a resolution of the cell width, 38 mm. The cells are always arranged in a symmetric layout, to ensure that the panel is balanced. A maximum of one group of cells is allowed to minimise harness requirements. The distance x_{cell} is the distance between the insert and first cell and it is measured in number of cells. Where possible, symmetry has been used to reduce the number of simulations required.

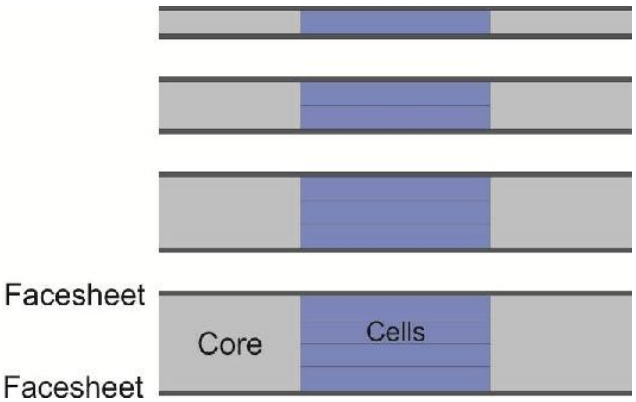

Fig. 3 The range of possible stack heights

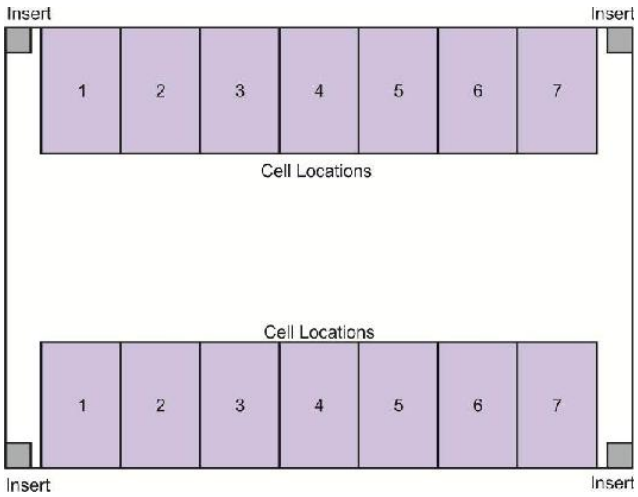

Fig. 4 The range of possible stack locations

V.FEM

The finite element model is made of only solid elements using ANSYS 12.1. The honeycomb core is not modelled directly as such a level of detail is not required. The core is instead modelled with solid elements that have the equivalent properties. The model is constrained by rigid elements that link the inserts to a point mass representing the vibration source. Fig. 5 shows one possible arrangement with the cells in blue and the inserts attached to the mounting.

VI. Optimisation Methodology

To provide the most useful information to the potential end user, the optimisation focuses on possible cell arrangements of a given number of cells. The most likely scenario to be faced is that of a designer being given a required capacity and wishing to know the best arrangement of cells to meet both capacity and mechanical requirements. Possible layouts are assed using two criteria:

- The effect replacing core with battery cell has on the performance of the structure.
- The loading experienced by the cells.

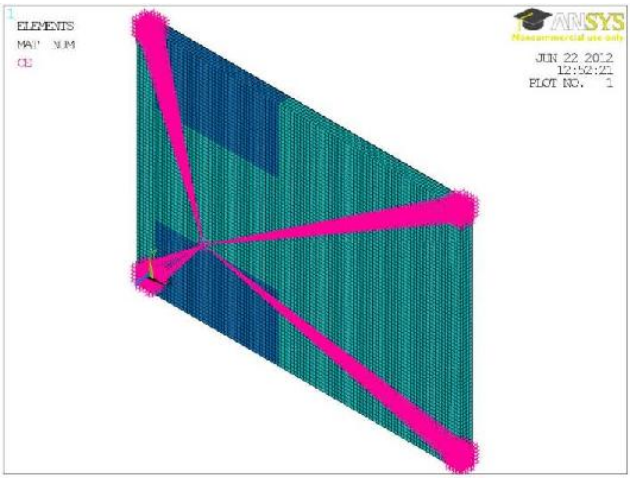

Fig. 5 The finite element model, with the top layer removed to reveal the core

The structural effects are measured by how the performance of the panel alters from its monofunctional state. This is done by performing a modal analysis of the panel and by exposing it to a sample random vibration environment. Increases in the natural frequencies of the panel will indicate that the cells have "improved" the panel as conversely; any decreases will indicate that panel's mechanical performance has been reduced. An analysis of stresses and strains that result from the random vibration will show similar effects, with increases in stress an indication of a weaker panel that has to compensate for the cells. Decreases in stress are an indication that the panel is stronger and mechanically better. As the modal analysis contains no loads on the structure, it is not a representative loading condition for the battery cells. Thus the stresses in the cells are considered only for the random vibration results. Analysis of this will allow definition of the best location to protect the cells from mechanical failure.

The random vibration profile is determined by the ECSS-E-10-03A [4] standard. For internal equipment mounted onto an external panel, the following regime is applied, from Table I of the standard. The panel has a maximum possible mass of 1.5 kg. This gives a total acceleration of 29.6 g_{rms}.

TABLE I
The Vibration Regime

Duration	Bandwidth	Levels
Vertical	20 – 100 Hz	+3 dB/octave
2.5 Minutes	100 – 300 Hz	PSD = 0.12 g^2/Hz X (M + 20 kg)/(M + 1 kg) = 1.032 g^2/Hz
	300 – 2000 Hz	-5 dB/octave

VII. Results

A. Single Cell

Fig. 6shows the possible arrangements for single cells. In this instance, there are four options as to where to place the single cell, all with a stack height of 1. Fig. 7 shows how the 1st resonance mode frequency and the cell Von Mises stress varies with cell position. It is important to note that the

complicated internal structure of the cells makes it difficult to determine the exact stresses the cells experience. It is preferable to refer to the Von Mises stress results as equivalent stresses as if the cell was a homogenous material. While this does prevent precise quantitative assessment, qualitative assessment can be carried out. From this, it can be seen that for best stiffness, as indicated by a higher first modal frequency, a position close to the inserts is preferred. For minimum stress in the cells, a central position is preferred.

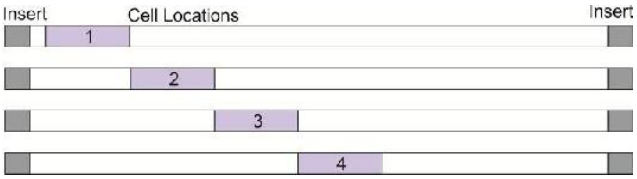

Fig. 6 Possible arrangements of a single cell

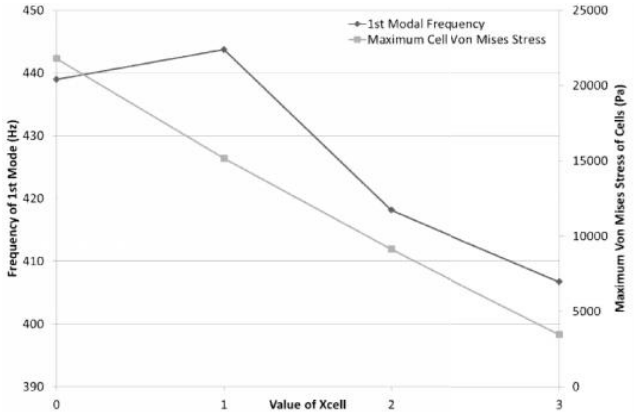

Fig. 7 Variation of cell performance with placement of a single cell

B. Two Cells

Fig. 8 shows the possible arrangements for two cells. All of the single cell positions with a stack height of two and all of the twin cells configurations with a stack height of one are assessed. Fig. 9 and Fig. 10 show that a stack height of two is preferred solution and that placement of the cell closer to the insert is preferred, but not too close. A reduction in first modal frequency is seen when the cells are in very close proximity to the inserts. This is due the poor mechanical properties of the cells weakening the panel in a crucial area, allowing it to flex more. The cells experience lower stresses in two height stack and when placed further from the inserts.

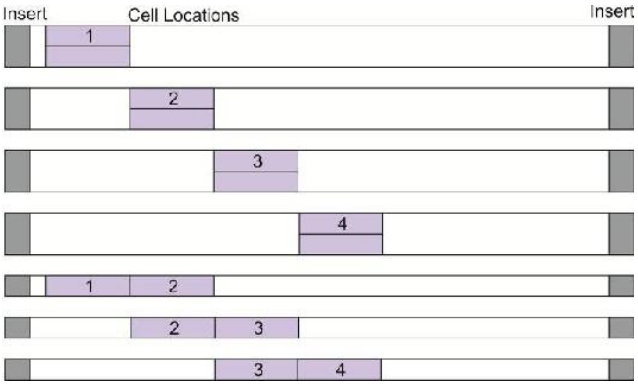

Fig. 8 Possible arrangements of two cells

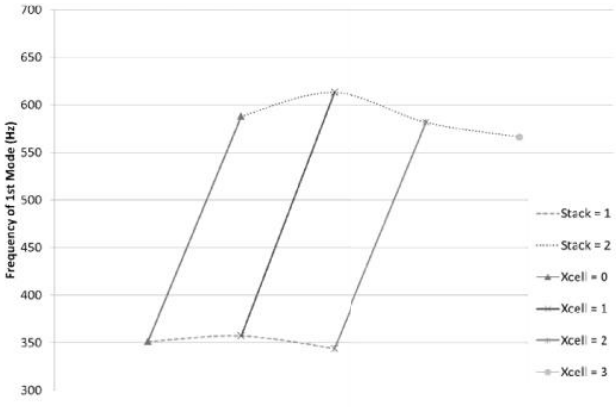

Fig. 9 Variation of frequency of 1st mode for a 2 cell system

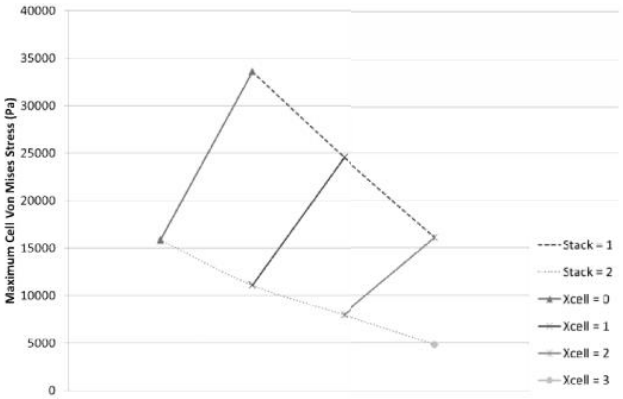

Fig. 10 Variation of maximum cell Von Mises stress for a 2 cell system

C. Three cells

Fig. 11 shows the possible arrangement for three cells. All of the single cell positions with a stack height of three and all of the triple cell configurations with a stack height of one are assessed. Fig. 11 and Fig. 12 show that a stack height of three is the preferred solution and that placement of the cell closer to the insert is preferred, but not too close that the cells weaken the area around the insert. The cells experience lower

stresses in three high stacks and when placed further from the inserts.

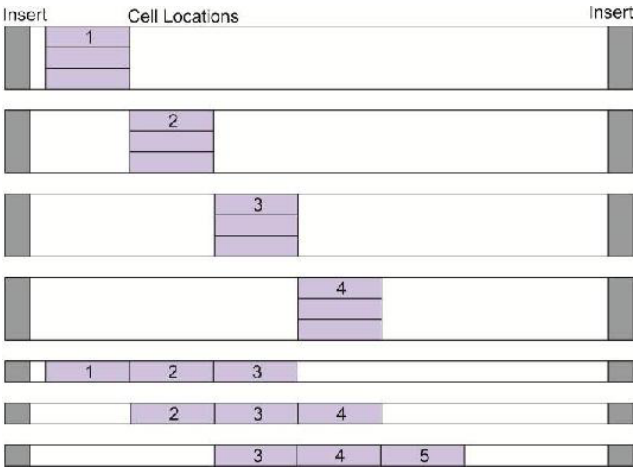

Fig. 11 Possible arrangements of three cells

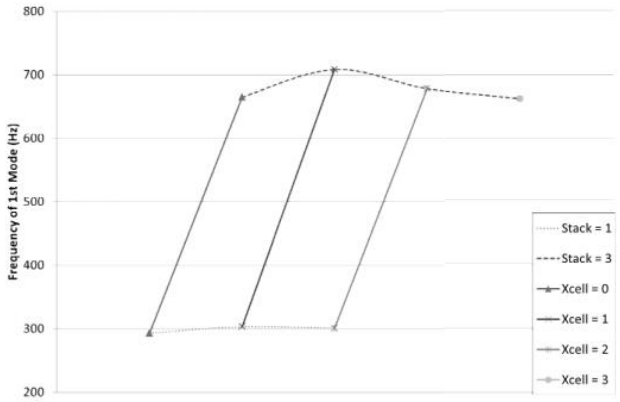

Fig. 12 Variation of frequency of 1st mode for a 3 cell system

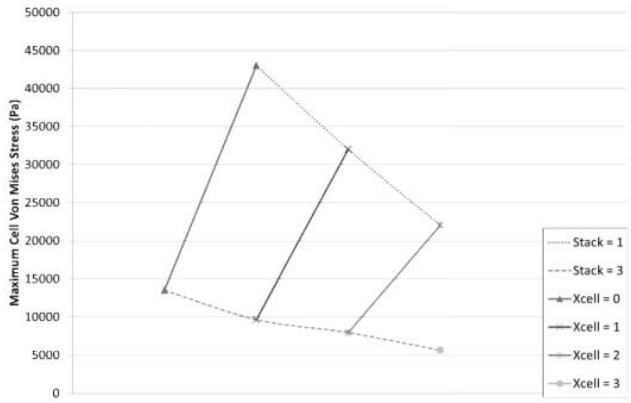

Fig. 13 Variation of maximum cell Von Mises stress for a 3 cell system

D.Four Cells

Fig. 14shows the possible arrangements for four cells. All of the single cell positions with a stack height of four are considered, as well as the all the twin cell positions with stack height of two and the four cell configurations. Fig. 15 and Fig. 16 show the changes in the first vibration mode and Von Mises stress. They show that a stack height of four is the preferred solution and that placement of the cell closer to the insert is preferred, but not too close that the cells weaken the area around the insert. The cells experience lower stresses in the four height stack and when placed further from the inserts.

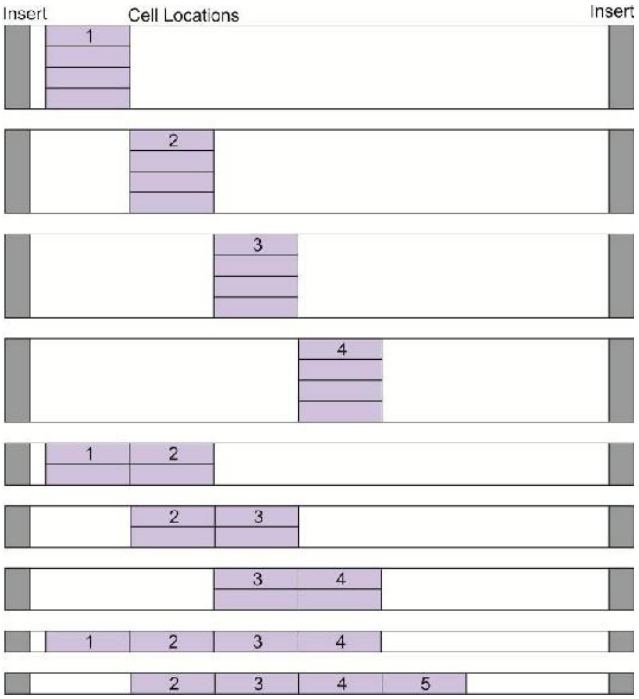

Fig. 14 Possible arrangements of four cells

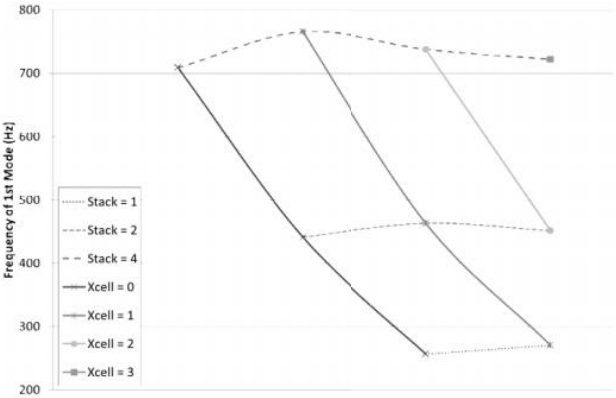

Fig. 15 Variation of frequency of 1st mode for a 4 cell system

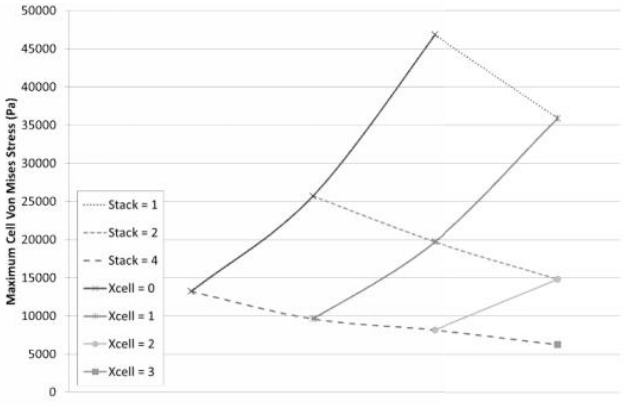

Fig. 16 Variation of maximum cell Von Mises stress for a 4 cell system

E. Six Cells

Fig. 17 shows the possible arrangements for six cells. The 6 cell configuration with a stack height of 1 is considered with the twin cells configuration in a stack height of 3 and the triple cell configurations at a stack height of 2. Fig. 18 and Fig. 19 show the variation in the 1st modal frequency and the maximum Von Mises stress the cells. They show that a stack height of three is the preferred solution and that placement of the cell closer to the insert is preferred, but not too close that the cells weaken the area around the insert. The cells experience lower stresses in the three height stack and when placed further from the inserts.

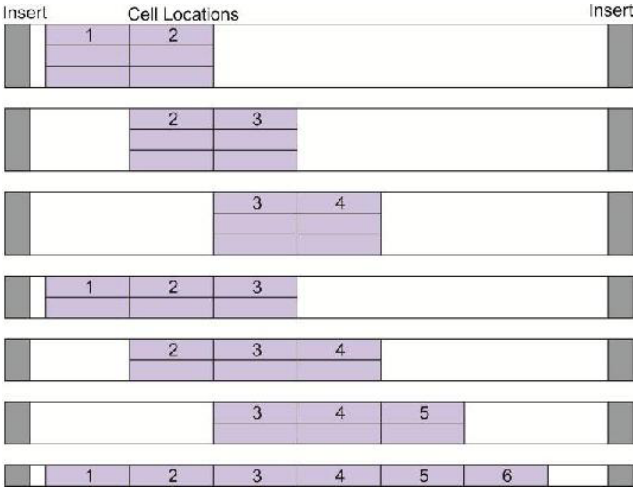

Fig. 17 Possible arrangements of six cells

VIII. Discussion

The results show that increasing the gap between the cells and the insert results in an initial increase in the frequency of the first mode as the structurally weaker cells are moved away from the insert, making the panel stiffer. When the cells are moved further towards the middle of the panel a reduction in the frequency is seen as the mass moves toward the centre of the panel where its effect is greater. The effect of adding more cells to the panel is to greatly reduce the resonant frequencies as the panel contains more mass. A greater cell stack height increases the stiffness of the panel, though this is most likely a function of the thicker core.

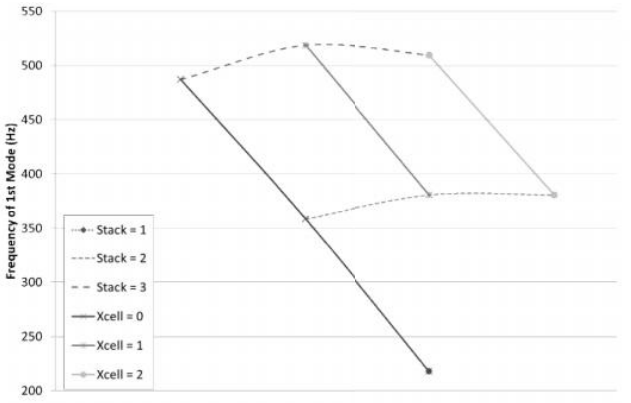

Fig. 18 Variation of frequency of 1st mode for a 6 cell system

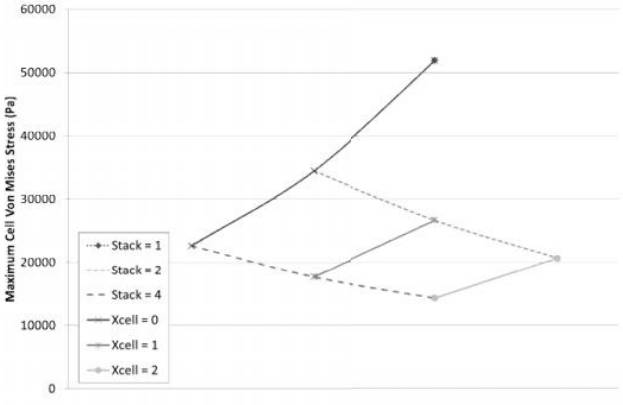

Fig. 19 Variation of maximum cell Von Mises stress for a 6 cell system

At low cell numbers, moving the cells away from the inserts has limited effect on altering the maximum stress in the panel. Panel stress is increased as the cells move toward the centre of the panel where the added mass as a greater effect. At higher cell numbers, moving the much larger mass of the cells away from the inserts reduces the stress more significantly as the panel takes advantage of the stiffer core material that replaces the cells near the inserts. The effect of more cells is to greatly increase the loading experienced by the panel as it has to support a larger battery mass. The effect of the stack height is interesting; for low cell numbers, the increase in stack height acts to stiffen the panel as the increased core thickness overcomes the added battery mass. At higher cell numbers, this is not true and the greater battery mass causes an increase in panel stress.

IX. Conclusion

Multifunctional power structures offer the potential for significant mass savings for Mars exploration missions. This paper has presented an optimisation study of commercial

battery cell variation of the concept. A numerical model was deployed to investigate the effects of increased battery capacity on the mechanical performance of the multifunctional structure.

This study of the best arrangement of a set number of cells reveals a conflict of interest. In all cases it is preferential for panel stiffness that the cells be placed only small distance from the inserts. However, to minimise stress in the cells, it is preferable to place them at the centre of the panel. The designer must trade-off between these factors. For both criteria, it is highly preferable that the stack height be higher as this increases the 1st frequency and reduces cell stress.

Consideration of this conflict of optimisation requirements will help the development of multifunctional structures with high efficiency. The study also highlights the key weakness in the concept, that off the poor mechanical properties of the cells, which limits greatly their contribution to the mechanical properties of the panel. Further work should both focus on the development of physical prototypes to experimentally test and verify these results and on the development of more robust battery solutions.

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