

Mechanical and electrical behavior of a novel satellite multifunctional structural battery

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A novel multifunctional structural battery (MFSB) has been designed using gel polymer lithium-ion (GPLI) batteries, carbon fiber reinforced polymer (CFRP) composite and polymethacrylimide (PMI) foam for satellite mass and volume reduction. Typical mechanical and electrical experiments were carried out and found that the designed MFSB can survive the vibration of spacecraft launch and mechanical load up to serviceable limit of either CFRP skins or PMI foams causes no electrical degradation of the embedded GPLI battery, presenting considerable potential for satellite application.

Keywords: Satellite, MFSB, GPLI battery, CFRP, PMI foam

Introduction

It has always been expensive to explore space¹, thus new technologies and methodologies are sought to lower this expenditure, and one of them is called Multifunctional Structure (MFS) mainly developed in the US at the end of the 1990's². Multifunction is an innovative concept that involves the development of new materials and devices and is capable of performing multiple functions within a certain system. MFS incorporates functionalities conventionally independently exist such as sensing, actuation, energy storage and the like to the primary structure of satellite³⁻⁴. Multifunctional Structural Battery (MFSB), as a kind of MFS, is the combination of energy storage device and satellite primary structure. Being embedded into satellite host structure, battery's purely structural packaging components and other parasitic elements like connectors become unnecessary and thus can be eliminated. Meanwhile, as the embedded battery is capable of carrying structural loads, some primary structure may also be removed. Therefore not only the satellite inside space is saved, but also, the total mass and probably volume of the satellite is reduced.

During the past decades, many research efforts about MFSB have been undertaken, involving conception⁵⁻⁹, feasibility assessment¹⁰, design¹¹⁻¹⁴, fabrication and performance characterization¹⁵⁻¹⁷ as

well as parameter optimization¹⁸. Aside from spacecraft, in many other structural fields, such as aircraft¹⁹, underwater unmanned vehicle²⁰⁻²¹, ground vehicle²² and even domestic buildings²³, integration of power storage and load bearing functionalities is mentioned and developed, all of which intend to enhance the efficiency of related components in terms of performance to mass, volume and cost ratio.

The main motive of this paper is to develop an innovative satellite structure that has both load bearing and power storage & supplying functions, which is called multifunctional structural battery (MFSB). Then its mechanical and electrical properties were tested and found that the designed MFSB can survive the vibration of a spacecraft launch and mechanical load up to serviceable limit of either CFRP skins or PMI foams caused no electrical degradation of the embedded gel polymer lithium ion battery, which meant that the design was feasible. The inspiring finds indicates that if designed properly, MFSB can present stronger mechanical characteristics.

Experimental

Materials

The embedded cells selected in this work are of the gel polymer lithium-ion (GPLI) type and were designed and manufactured in National Univ. of Defense Technology (NUDT). Unlike the widely used space cells, such as Cd-Ni battery, H₂-Ni battery etc., which have liquid electrolyte and are deposited in cylindrical metal casing and therefore are rather

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heavy, GPLI cells have quasi-solid electrolytes and therefore good load bearing capability. Moreover, their feasibility of being applied in space missions was assessed²⁴ and the results were promising.

Since carbon-fiber-reinforced composite structures are widely used in aerospace industry due to their advantages of having high specific strength and stiffness and strong design ability, laminated carbon/epoxy fabric was chosen as the face sheet. The face sheets were made of layers of carbon fiber plain weave.

Polymethacrylimid (PMI), a kind of rigid and closed-cell foam of 75 kg/m³ density (from Evonik Degussa, Germany), having good workability and space adaptability²⁵, which can simplify the sandwich composite structure fabrication considerably and foremost offer enough structural resistance against battery expansion caused by pressure difference between the inside and outside of the GPLI battery, was chosen as the sandwich core.

Configuration

The proposed multifunctional structure-battery configuration is shown in Fig. 1. The GPLI cell is embedded in sandwich structure and used as part of sandwich core. Besides, cables that connect cells in series or parallel ways as well as power control unit (PCM) and other equipment that belongs to satellite power subsystem are also inserted in the sandwich core.

From a view point of structure, the MFSB sandwich core can be honeycomb, foam, or truss, selected by highest strength-to-density or stiffness-to-density ratio. As for the embedded lithium cells, shape can be manufactured as prismatic or strip according to the inner space of the sandwich structure that could be made use of. Configuration, can be designed as flat panel style or hetero-type conforming to the shape of host structure, thus promising highest

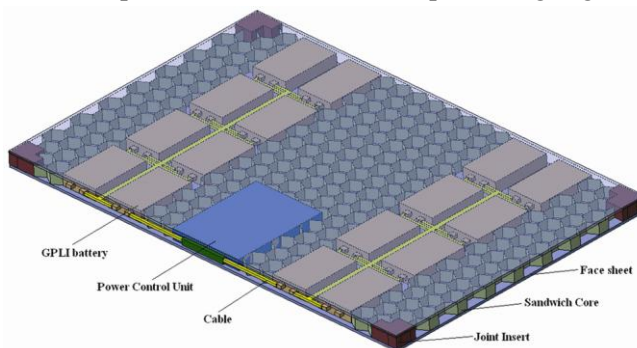


Fig. 1—Schematic of multifunctional structural battery

integration between structures and batteries. Location can be distributed in a regular array or just near the power consumer to provide localized and autonomous power in remote locations, thereby eliminating heavy power transmission cables to and from centralized power sources to save space and weight. All the above flexibility and choices make this MFSB concept rather appealing and advantageous.

The MFSBs were designed as beam prototype to assess the conception's potential for satellite application and within each MFSB, a GPLI battery was framed in the geometric center of MFSB within PMI foam channels and then bonded between a flat laminate on one side, and a conformal laminate on the other side. Besides, aero cable was selected for power bussing.

Sixteen specimens were prepared, including eleven MFSBs, and the rest were unfunctional specimen (UFS). The dimensions of the experimental samples were 300×80×20 mm (length×width×thickness). Both upper and lower face sheet thickness was 2 mm, consisting ten layers of carbon fiber plain weave, each of 0.2 mm thickness, and the foam thickness was 16 mm. The selected GPLI cell was designed and fabricated in NUDT, with dimensions of 105×67×6.5 mm and capacity of 6.5 Ah.

Among the eleven MFSBs, three had GPLI battery just physically laid in the foam core cavity because the GPLI battery's mechanical property was not clearly understood and in this way the embedded GPLI battery could endure a lighter loading in the forthcoming exploratory mechanical tests, and these three MFSBs were termed as series-C. The other eight MFSBs were all bonded to the ambient foam core and CFRP face sheet using epoxy glues, promising a continuously load transferring path within the MFSB and thus showed better mechanical performance that can be seen in the following mechanical tests. According to the different types of exterior loads, namely vibration, bending or compression, these eight MFSBs were divided into three groups, series-B, series-D and series-F. Five UFSs were fabricated to provide a baseline for comparing mechanical performance, namely series-A and series-E. Detailed exterior load conditions are summarized in Table 1.

Vibration Testing

Vibration testing of MFSB was performed due to the dynamics environment involved in the launching of satellite to investigate survivability of the selected material system and processing technology and to

determine the possible failure modes of the design. As frequencies exciting the structure above 2000 Hz are generally negligible, the significant region of interest in terms of vibration is from 20 to 2000 Hz. The random vibration profile was chosen to simulate a typical spacecraft launch. The profile has a total acceleration of 13g, a total duration of 6 minutes (2 minutes for each of the three principle axes). Since the dynamic shaker can vibrate only forth and back, three MFSBs were fixed to the dynamic shaker along the length, width and thickness directions in order to evaluate them simultaneously.

Three-Point Bending

To find out the variation of structure loading bearing capability caused by embedding of GPLI cell, as well as the GPLI cell's utmost ability of loading and deformation endurance, three-point bending test was performed on both the MFSBs and their unfunctional counterparts in a procedure set by GB/T 1456-2005. The specimens were tested at room temperature on SANS test system with a 10 kN load cell. The tests were run in a displacement control mode at a cross-head speed of 1 mm/min.

Compression Testing

Compression testing was conducted also using the SANS load frame to create a different load and deformation style in order to evaluate the GPLI cells' behavior under load and deformation.

Table 1—Loading conditions for all the specimens
(N stands for not applied, Y means applied)

Specimens	No.	Vibration	Three-Point Bending	Compression
UFS	A-1	N	Y	N
	A-2	N	Y	N
	A-3	N	Y	N
	E-1	N	N	Y
	E-2	N	N	Y
MFSB	B-1	Y	Y	N
	B-2	Y	Y	N
	B-3	Y	Y	N
	C-1	Y	N	N
	C-2	Y	N	N
	C-3	Y	N	N
	D-1	N	Y	N
	D-2	N	Y	N
	D-3	N	Y	N
	F-1	N	N	Y
	F-2	N	N	Y

Electrical Testing

To evaluate the influence of vibration, bending and compression on cell performance, cycle-life and capacity verification were performed both before and after mechanical loading (because of batteries don't work during satellite launching, no electrical testing was carried out when the mechanical loads were putting on). The tests were carried out under a regimen of constant-current, constant-voltage (CC-CV) charge mode with a taper voltage of 4.2 V, a charge rate of 1 C, and a charge time of 3 h, and constant-current (CC) discharge mode with a discharge rate of 0.2 C and a cutoff voltage of 2.7 V, according to the manufacturer.

Results and discussion

Fig. 2 shows the load-deflection curves in bending tests for all the specimens, multifunctional and unfunctional, except E-series and F-series. It can be seen that A-series specimens present the strongest load carrying ability, while B-series, C-series and D-series all declined, though to different extent, which means that the insertion of cell weakens the primary structure. Comparing to A-series specimens (unfunctional counterparts fabricated as mechanical reference), the apparent bending stiffness (slope of the load-deflection curve) of B-series and D-series declined approximately 12.5%, while C-series fell about 50%. As for the failure load, C-series declined most severely, about 45%, whereas it is 19.5% for B-series and D-series, that's mainly because that there was no bonding adhesive between the embedded GPLI cell and its ambient structure parts, which destroyed the structural integrity of MFSB and broke the load transmitting path off. This can be clearly seen from the different behavior

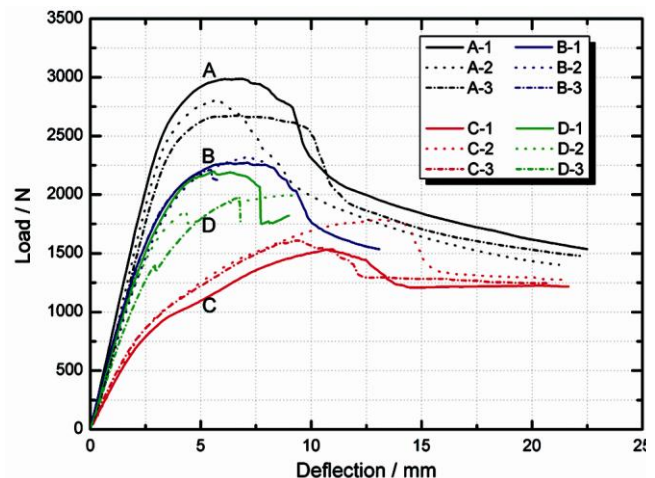


Fig. 2—Load-displacement curves in Three-Point Bending of A-series to D-series specimens

of B-series and D-series, as they were designed and manufactured almost the same as C-series except that bonding glue was used between their inner cells and structure parts. As concerns of B-series and D-series, they exhibited nearly the same mechanical properties, though B-series were vibration loaded additionally, from which it can be concluded that the pure vibration has little or no effect on the MFSB, of course, just from a view point of mechanics. Meanwhile, this behavior also indicates that the selected materials and processing techniques are feasibility to survive the launch vibration. As for the longitudinal compression, E-series are specimens without GPLI cells and show stronger load bearing ability. Whereas, MFSBs, that is F-series, show similar response behavior, with a peak value reduction of only 8.3% meaning that the insertion of GPLI cell doesn't break the integrality of the sandwich structure, as regards whether the cell can still normally store and supply power, capacity verification performed later will give explanation.

Electrical performances of all the MFSB specimens before and after exterior loadings are presented in Fig. 3. Apparently, the change in discharge curves for the given discharge rate was almost the same for specimens C-2 and C-3, indicating that pure vibration had very little effect on cell electrical property. As for specimen C-1, along with the discharge process, a slight decline in discharge voltage and capacity appeared. Taking into account of the cell performance dispersion caused by manufacturing, this phenomenon may be attributed to self-discharge during the capacity verification before and after vibration testing.

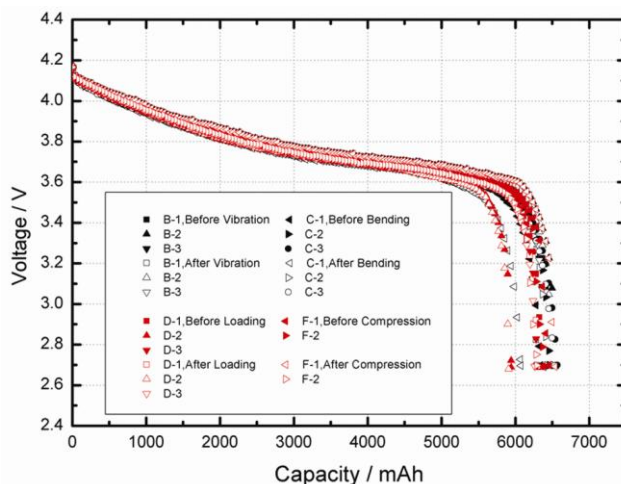


Fig. 3—Electrical performance of specimens before and after exterior loadings: B-series (compound loading), C-series (vibration), D-series (bending), F-series (compression)

Besides, Fig. 3 also illustrates discharge characteristics of D-series specimens before and after three-point bending tests. It can be seen that capacity of each specimen kept pretty good after bent loading compare to its unloading condition, suggesting that bent loading has almost no influence on electrical property of the designed MFSB, although the MFSB underwent quite tremendous deformation or even was destroyed. As for B-series specimens, which suffered a severe mechanical loading, that is simulated vibration plus three-point bending. The obtained nearly overlapped curves indicate that the MFSBs were strong enough to endure such a server loading condition. Electrical checking results of F-1 and F-2 specimens before and after compression are also presented in Fig. 3. When the compressive load was applied, even if the MFSBs themselves were ruined, however, the embedded cells remained their capacity perfectly, suggesting a potential to survive larger loads and deformation.

Conclusion

To achieve a great satellite mass reduction, a novel multifunctional structural battery concept was proposed in this paper. And an exploratory study was performed, involving MFSB concept design, manufacturing, mechanical and electrical checking. The main conclusions are as follows:

- (1) After encapsulating gel polymer lithium ion cell into foam core sandwich structure, the structure's load carrying ability presented only a finite decline, indicating that if designed properly, this kind ability loss can be lowered or diminished.
- (2) From a view point of cell capacity, mechanical loading up to serviceable limit of either CFRP skins or PMI foams caused no electrical degradation of the embedded gel polymer lithium ion battery, nor did simulated rocket launching vibration, which proved that the designed multifunctional structural battery have tremendous potential and feasibility to be applied on satellite. With improved location choice and connection manner as well as optimized manufacturing processes, the GPLI cells' capability to bear mechanical loads could be further exploited and utilized and thus multifunctional structural battery of higher advantage can be obtained. And the goal to make satellite smaller and lighter of course can be better satisfied.

The novel multifunctional structural battery developed in this paper accomplished a perfect

combination of CFRP, PMI foam and GPLI battery, showing the potential of reducing satellite mass and volume greatly, then satellite payload can be increased considerably.

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