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Detailed structural design and corresponding manufacturing techniques of the MASCOT Landing Module for the Hayabusa2 mission

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The DLR Mobile Asteroid Surface Scout (MASCOT) is an approximately 11kg shoebox-sized lander platform developed in cooperation with CNES and JAXA for the Hayabusa2 (HY-2) Asteroid Mission, which was launched successfully in December 2014 to the C-class asteroid 1999JU3. Therefor the MASCOT Landing Module accommodates 4 instruments (camera, magnetometer, spectrometer and radiometer) of 3kg in total. Further it has a mobility mechanism for up righting and hopping, integrated into the common electronic box' housing.

The MASCOT structure itself consists of two separate main parts, the Mechanical & Electrical Interface Structure (in the following called Interface Structure) and the Landing Module. The Interface Structure is mainly made of unidirectional carbon fibre reinforced plastic (CFRP) struts, forming a highly stiff 680g weighting framework that is fixed in a cutout of one of the HY-2 side panels and encloses the Landing Module. To fixate the Landing Module within the Interface Structure one central connection bold pulls the Landing Module into four Interface Structure-sided bearings.

The focus of this paper is on the only 550g lightweight, cubic Landing Module with its structural (detailed) design and corresponding manufacturing techniques. In contrast to the Interface Structure, the Landing Module is a CFRP/foam sandwich framework structure. Its architecture is realized in such a way that all interface loads from heavier subunits are only introduced as in-plane loads into one of the sandwich walls. The CFRP/foam sandwich struts have mainly unidirectional face sheets that are locally combined with ±45° CFRP fabric plies to account for local stress concentrations. Furthermore the fabrics provide enforcement against shear loads and connect adjacent framework walls to each other. At load bearing points the foam core is locally replaced by solid CFRP blocks, which provide sufficient out-of plane stiffness and an enlarged area for out-of plane shear load introduction. One of the six Landing Module's outer sides is closed with a detachable Aluminium sandwich radiator that serves at the same time as main integration and late access opening. To interface the radiator structurally and thermally to the other foam sandwich walls a combined solution with and without inserts was applied. Besides to these mechanical aspects also cleanliness and contamination control aspects, e.g. how the foam core was protected and handled, are covered. The paper will close with a lessons learned section, covering the manufacturing and cleanliness aspects to be considered for a CFRP-sandwich structure.

I. MASCOT SYSTEM DESIGN

The DLR Mobile Asteroid Surface Scout (MASCOT) is an approximately 11kg shoebox-sized lander platform developed in cooperation with CNES and JAXA for the Hayabusa2 sample return mission heading to the Cg-class asteroid 1999 JU3[1]. It was successfully launched in December 2014. MASCOT is dedicated to support Hayabusa2 with landing site selection and to enhance it with in-situ surface science capabilities. Therefore it carries four instruments weighing a total of 3kg (see Figure 1). These are MicrOmega (near-infrared hyperspectral microscope), MASCam (camera in visible range), MARA (radiometer) and MAG (magnetometer). For the purpose of up righting and relocation on the asteroid's surface the lander's common electronic box (E-Box) houses a mobility mechanism, which is based on a tungsten mass eccentrically mounted at the end of a step motor-driven momentum arm. Furthermore the E-Box provides on its top side a late access interface (I/F) for the battery sub-system, which provides for 16 hours electrical power during MASCOT's operational phase on the asteroid's surface. 16 hours correspond to two asteroid days.

The MASCOT system itself is subdivided in two main structural parts[23], the box-shaped Landing Module, housing all experiments and sub-systems, and the surrounding Mechanical and Electrical Support

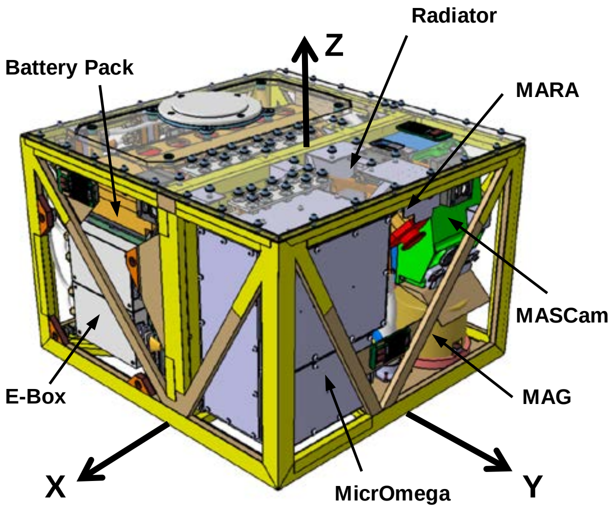

Figure 1: Landing Module accommodation (removable radiator shown transparent; insulation foils omitted).

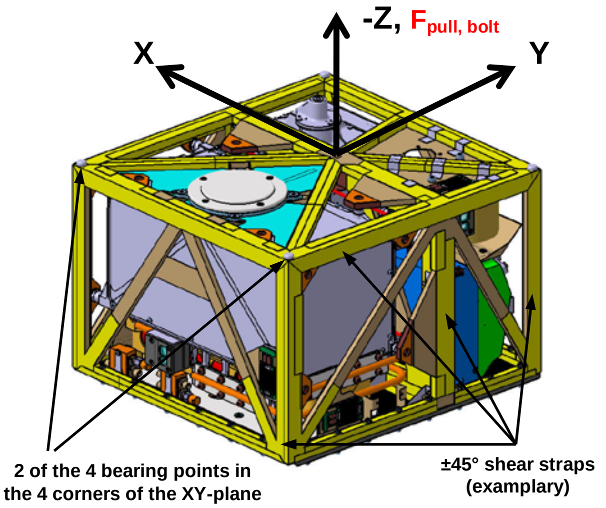

Figure 2: Landing Module assembly (up-side down) with bearing points and main load introduction $F_{Pull,bolt}$ (insulation foils are omitted).

Structure (in the following called Interface Structure). Both are constructed as highly stiff and lightweight composite framework structures having together a total mass of around 1.4kg. This paper focuses on the detailed structural design concept of the 550g light Landing Module and corresponding manufacturing techniques. Especially design details, driven by cleanliness and instrument requirements, are presented. A lessons learned section will close the paper and discuss the promising, but also difficult design aspects with a view to possible future MASCOT derivatives.

II. THE SANDWICH FRAMEWORK STRUCTURE

From the beginning on the MASCOT system was facing very tight and demanding mass constraints. Hence, to meet these requirements the first structural & thermal model (STM) in phase B was an extreme and very delicate concept. In order to improve the structure's handling for integration purposes, to incorporate additional sub-system's needs and to face increased structural requirements (in terms of mechanical and thermal loads) several design details were introduced during Phase C. However the basic structural concept remained. This basic concept foresees for the Landing Module a framework structure based on 6 separate CFRP/foam sandwich walls. Each framework wall consists of a 5mm thick foam core and unidirectional (UD) CFRP face sheets (see *Table 1*). Accordingly the structural design makes maximal use of the highly orthotropic material properties by aligning the fibres mostly in the struts' axis. In contrast to the framework walls, the removable radiator plate is designed as an aluminium sandwich plate, mounted with screws to the structure's sandwich walls. The main load for the Landing Module is introduced into the X/Z-Middle Wall plane (see Figure 2 and Figure 6) by a bolt exactly along the –Z-axis, connecting the Landing Module with the Interface Structure. The bolt is pulling with 2500N to keep the Landing Module firm in the Interface Structure. From the bolt, the load is guided through the sandwich framework to four bearing points in the corners of the Landing Modules' –Z-sided Bottom Plate. Here the bearings fit the Interface Structure again (see Ref.[2] and section II.II).

Also the (reaction) forces of payloads (P/L) and heavier sub-units weighing > 0.5kg are introduced in the wall's in-plane directions and redirected respectively. A redirection is necessary because of to the poor out-of plane properties of the sandwich framework walls. To cope with this, basically three different approaches are applied, that will be discussed in the upcoming paragraphs:

1. Redirection out-of-plane loads from one wall into an adjacent, normal orientated wall (see paragraph II.III)
2. Fixing the P/L or sub-unit to more than one I/F-wall (see paragraph II.IV)
3. "Wrapping" struts with two additional U-shaped plies that form a rectangular closed cross section (see paragraph II.V)

Before, paragraph II.I will introduce into the detailed framework design and manufacturing including an application-specific solid CFRP insert concept.

Part/Component	Material
Framework walls	M55J (UD)/LTM123 + Rohacell IG-31F
Shear straps	M40J (0°/90° fabric)/ Scheufler L160-H163
Radiator	EN AW 6082-T651 + Plascore PAMG-XR1-3.1-18-0007-P-5052

Table 1. Landing Module's material composition.

II.I Detailed framework design and manufacturing

This section will introduce in the detailed build of the Landing Module's sandwich walls. Furthermore the implementation of two different kinds of inserts will be explained. One insert type takes up in-plane loads and the other one out-of-plane loads.

The Landing Module framework is assembled from 6 individual sandwich walls. These are connected to each other via L-shaped shear straps made from M40J CFRP fabric aligned with a ±45° angle relative to the strap's axis (compare Figure 2 and Figure 6). The framework walls itself consist of two facesheets with M55J UD prepreg (pre-impregnated) plies, which are mostly aligned in the framework struts axis (see Figure 3). The core is made from Rohacell IG-31-F closed cell foam. To manufacture the walls, first the face sheets are draped by the help of moulds as shown in Figure 3. The moulds allow a draping of UD-plies that are intentionally slightly longer than required. This eases the draping process and ensures that each ply can be draped with maximal length till the actual edge. Exceeding ply ends are removed carefully after gluing the face sheet with the core. At regions where interface loads from sub-systems or payloads are introduced into the framework a local strengthening and load distribution with additional ±45° plies is required. Figure 2 and Figure 6 show exemplarily how this is realized for the E-Box mounting points at the +X Side Wall. On the left side (A) two first ±45° plies (still with backing paper) can be spotted. The connecting vertical UD ply is pending. In the middle (C) another mounting point ply is highlighted while at the +X Side Wall's fourth ±45° ply position (B) no ply is draped yet.

In some parts of the sandwich walls the framework struts are very slender (5-10mm) and thin (5mm). Hence a foam core (Figure 4) is used instead of a honeycomb, because it may happen that at some areas only one complete honeycomb waffle may remain between the face sheets of the very slender struts. This is not enough for a firm connection between face sheets and core. Also it makes handling for the manufactures very difficult. After the face sheets are cured the foam core is pre-prepared. This includes marking the areas for the later insert replacements by the help of drawings, but also of the actual face sheet, which has to fit exactly the positions of the inserts.

There are two types of inserts used, an in-plane and an out-of-plane type. The latter one replaces the foam core where it alone is not able to carry the required normal forces induced by the screws, that fix the P/Ls and subsystems to the structure. In order to keep the P/Ls and sub-systems firmly fixed, normal forces in a small kN range are applied, which then result in a compression stress on the foam core itself. But instead

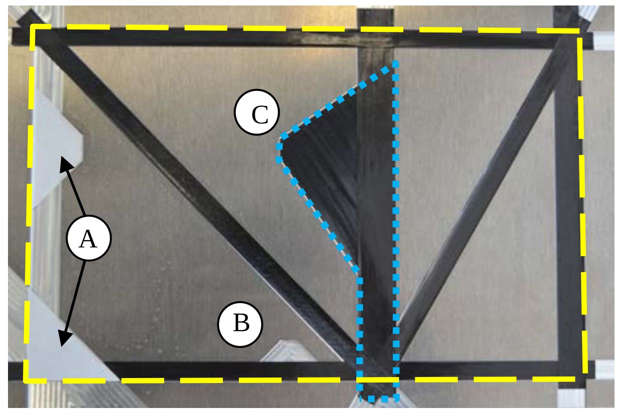

Figure 3: Face sheet draping of +X Side Wall into the mould. Blue highlighted a partially covered ±45° plie, that distributes the loads introduced at the E-Box interface into the vertical strut. In yellow the final face sheet's outline contour after exceeding plie ends will be removed.

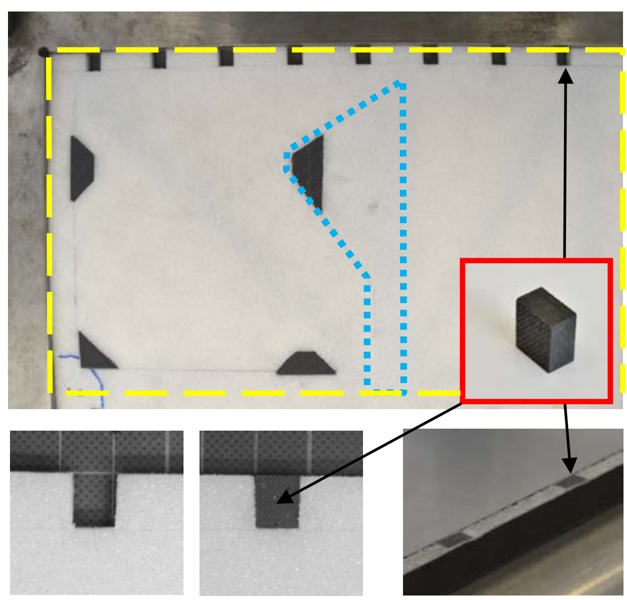

Figure 4: Foam core of the +X Side Wall. The blue marked area indicates how the face sheet shown in Figure 3 will be placed. The details show an exemplary radiator insert (in-plane type) and its placement within the sandwich.

of using “standard” Aluminium inserts, at each interface point the foam is cut out and replaced by a solid quasi-isotropic CFRP block made from a stacking of M40J fabric. After the cut-outs are done and the inserts are fit, one face sheet is attached to the foam plate. In a second step the inserts are glued in the corresponding foam cut-outs and subsequently the second face sheet is added. For all glued connections the same structural adhesive is used. In a later manufacturing stage, when the complete framework wall structure is assembled, additional strut stiffening elements (paragraph II.V.) et cetera are added. In the end a borehole pattern of the corresponding interfacing parts is used to drill through holes through the sandwich struts with the CFRP block inserts.

In contrast to the P/L interfaces the radiator inserts are of in-plane type, id est the fore is introduced parallel to the face sheets. As the out-of plane inserts also the in-plane ones have only a through hole. Hence an additional nut must be glued at the opposite end from where the screw and the radiator are fixed, respectively (see Figure 5, bottom right). By this the insert is clamped between the nut and the radiator. The load path is then a normal load introduced by the screw/nut into the insert and form there again via shear in the face sheets. The fix the nut it is glued on the strut and secured with a hat-shaped CFRP bracket that clamps the nut from two sides for additional torque support (see Figure 5, top right). Finally, for cleanliness reasons, the open space between nut and hat-bracket is filled with a little amount of structural adhesive in order to avoid dust accumulation. This insert design has several advantages. It is easy in manufacturing, it is cheap, it is lightweight and it provides sufficient out-of-plane and sub-systems’ interfaces. In order to cope with this, three different design solutions are realized for the Landing in-plane stiffness for both interface types (P/Ls and

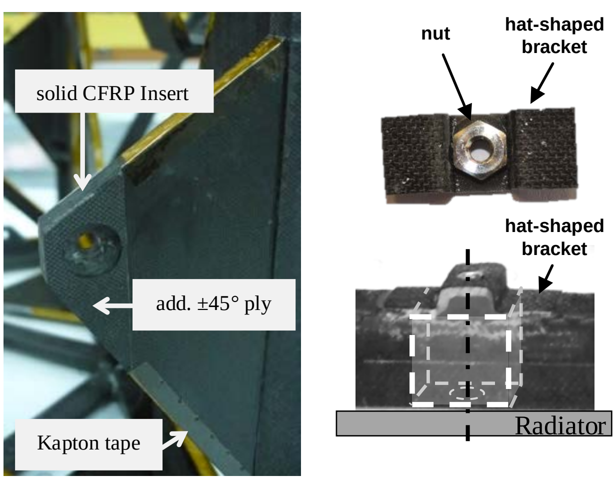

Figure 5: Details of countersunk E-Box mounting point (left) and radiator I/F (right). The I/F consist s of a solid CFRP block w/ through hole and a glued nut.

radiator). The drawback of a slightly wrong positioning during manufacturing is compensated by the fact, that the actual through hole is only drilled or bored up when all sandwich walls are already assembled. Hence a precise in-plane positioning is realised. To countersink the E-Box I/F holes, which is required to keep the Landing Module’s envelope, an additional ±45° fabric ply (see Figure 5) is added on top of the UD ply. This avoids pulling out fibres from the beneath UD ply during drilling. Although the solid blocks have quiet some surface area to transfer out-of-plane loads via shear in the foam, this for its own is not enough to carry the normal loads occurring at MASCOT payloads’ and subsystems’ interfaces. In order to cope with this, three different design solutions are realized for the Landing Module. These are further described in the following sub-sections.

<u>II.III E-Box mounting</u>

The electronic box is together with the on top mounted battery pack and the flanged mobility mechanism the heaviest and biggest sub-system package in the landing module. It occupies basically more than a half of the available space in the Landing Module. At the same time this is actually one of the advantages in the way of how the E-Box is mounted. The thin and slender sandwich struts offer only a limited area for load uptake and especially the delicate diagonal struts are designed for tension loading only. Also, the loading of a sandwich is preferably in the face sheet’s plane due to the fibres’ high stiffness and strength. As the E-Box is “so big” it actually allows positioning its interface points in mostly structurally favoured places, i.e. in corner points, close to the other struts’ axes and in their corresponding plane. The E-Box has three sides interfacing the Landing Module’s structure. These are the two side walls (-X and +X) and the bottom plate (-Z). With overall twelve short fittings close to the E-Box edges and corners, it is possible to distribute the occurring loads in three independent directions, id est four fittings for each direction. On the Landing Module’s side it is a bit more difficult. To bring the loads into the sandwich the aforementioned CFRP blocks are replacing the foam core. Further the interface points (through holes) are not placed exactly in line with the struts’ longitudinal axes, so they do not interrupt the main load path within CFRP UD struts. On the other hand this requires that the loads from the interface points must be guided by the +/-45° plies (compare to Figure 3 and Figure 4) into the UD struts. Figure 6 visualises that for the aimed in-plane loading of the sandwich walls only the +Z-interfaces on the Bottom Plate (in the picture at top side) can take up all the loads in x-direction. In contrast the four fittings at the Side Walls cover in pairs the Y- and Z-direction. The –Z-sided fittings introduce the loads into the Side Wall’s

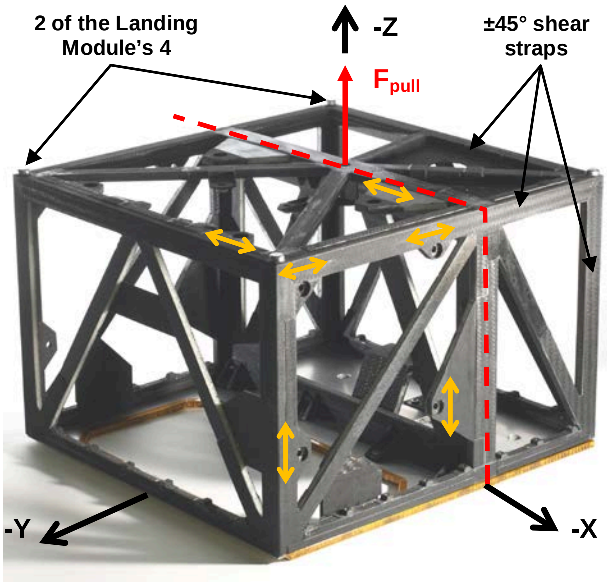

Figure 6: Landing Modules' structure upside-down with E-Box interfaces and Middle Wall plane (dashed red line) with main load introduction F_{pull}.

strut close to the Bottom Plate, whereas the +Z-sided fittings introduce loads occurring in Z-direction into the structure. Especially the latter ones as well as the bottom ones next to the middle wall needed a wide v-shaped extension. The extensions angles are designed in a way that enough continuous ±45° fibres run from the E-Box interface point to the adjacent strut for sufficient load redirection. In Figure 3, for example, one of the corresponding ±45° plies is highlighted.

II.IV MicrOmega & MASCam P/L interfaces

Figure 7 shows the lander from top side and without the detachable radiator plate. In the foreground of the Middle Wall there is the E-Box compartment and on behind the P/L compartment. From left to right the (-Z-sided) I/F brackets of the MicrOmega (1), the MARA (2) and the MASCam (3) instrument can be spotted, in which for MicrOmega and MASCam exactly the same I/F concept of normal load's distribution is applied. Because of the very limited space the two latter brackets are pointing in opposite directions.

This concept allows to introduce almost all loads in the sandwich wall's in in-plane direction and also close to the struts axes. A different concept to distribute the (out-of-plane) loads is followed for the design of the payload interfaces at the Middle Wall.

Exemplarily, the MASCam I/F is described in more detail next. Therefor Figure 8 shows a close-up of the MASCam support bracket, when looking in the blue arrows direction indicated in Figure 7. The brackets connect the payload I/F at the middle wall (point A) with the radiator plate (point B). Hence, the normal loads introduced at point A are directly redirected through the CFRP brackets and then further transferred as shear load and distributed in the radiator plane. To redirect the loads, the brackets are made from two separate U-shaped parts with 0°/90° and ±45° orientation, respectively, that are glued together (see Figure 8, bottom right). Because the radiator is detachable for integration purposes, the triangular-shaped brackets are integrated at the same time as the instruments. Considering the exemplary position in Figure 8 the instrument's feet and the CFRP brackets are fixed with the instrument's main screws in point A first. The connection to the screw mounted radiator in point B is only fixed in the end. Hence the brackets have glued nuts in point B, which keeps them firm in position without extra tool support and so allow torqueing the screwed connection form the other side, i.e. when the radiator is attached. Again it is (very) important for the realisation of these interfaces that the instruments are of the same dimensional scale as the Landing Module structure. This allows positioning the interface points in

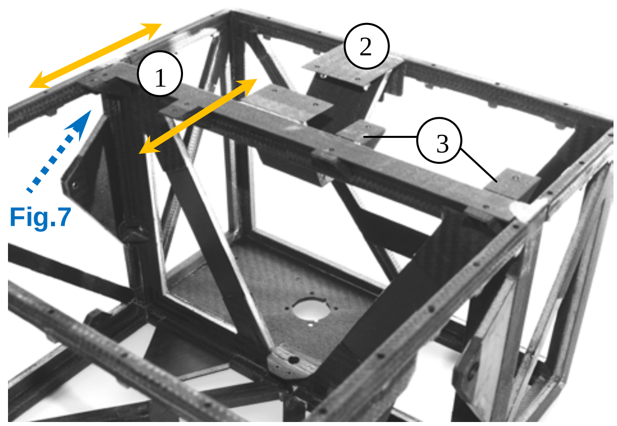

Figure 7: Middle wall with MASCam (1), MARA (2) and MircOmega (3) support brackets.

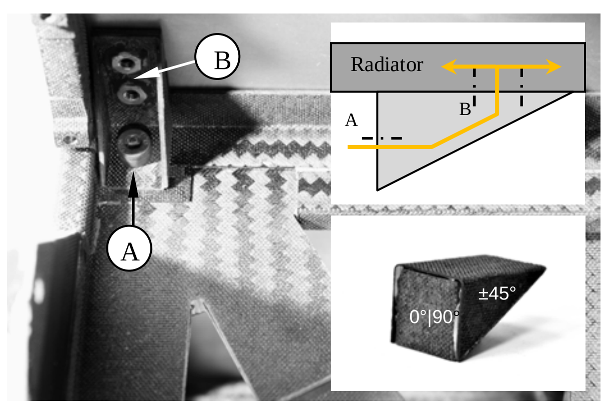

Figure 8: Detail of MASCam support bracket as build in, before drilling and assembly (lower right) and with load path (top right).

struts and comes with the “side effect” of closing not is formed. This adds torsional and bending stiffness to the only the cross section profile, but also the open foam of the struts’ corner points and in less loaded areas out of the load path respectively. All P/Ls and subsystems which have a “non-preferable” dimension profit from their low weight which makes dedicated load paths and more sophisticated load distribution less important. As an example the +Z-sided round patch antenna and its corresponding I/F design are introduced in the next paragraph.

II.V U-profiles for strut’s stiffening

The interfaces of the +Z-sided round patch antenna for instance (see sketched red circle in Figure 9) are rather low loaded. The diagonal struts that support its interface brackets are “wrapped” with two U-profiles, so that a closed rectangular cross section the sandwich in these areas. The actual interface requires four additional CFRP brackets.

III. CLEANLINESS & CONTAMINATION CONTROL

A major drawback of the foam core used in the landing module’s sandwich walls is its inherent porosity. When the foam between the framework struts/face sheets is removed, as described in the previous section, a large number of cells are cut open and little foam flakes are created. Many of these remain at and on the foam respectively and are difficult to remove without generating new particles. The same happens during later the manufacturing process, when parts are handled and even during assembly, if no counter measures are foreseen. Moreover the cut cells can collect dust (e.g. CFRP particles) or absorb water and other substances from the environment during parts manufacturing. Besides such ‘macroscopic’ contamination, the foam itself contains molecules that are released when exposed to high temperatures and/or vacuum as the gas pressure of the ligated molecules gets high enough to escape (outgassing). Hence the outgassing properties of the foam and the CFRP material were already analysed in phase B. The result for the foam only was, as expected, that without any measures an application in the spacecraft structure would result in an unacceptable high outgassing rate. Both, outgassing and water absorption/release are usually very high for foams, whereas water is considered to be less critical. Finally it was decided to use the foam for the reasons elaborated in section II.I and to apply adequate counter measures. Step by step several measures were implemented for the MASCOT Landing Module structure’s manufacturing as well as for the post-manufacturing phase. The experiences

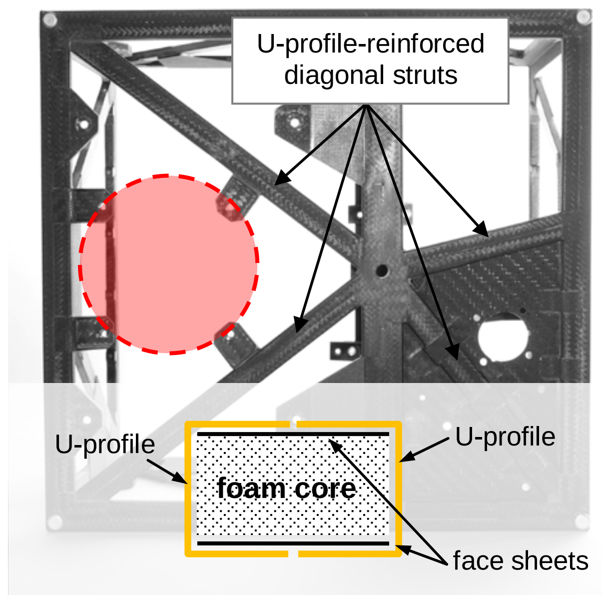

Figure 9: +Z-side view - patch antenna (sketched red circle) flanged to diagonal struts and detailed cross section sketch of the U-profile reinforced diagonal struts.

gained in the STM manufacturing were incorporated in the later EQM (Engineering Model) and FM (Flight Model) manufacturing or refined where necessary.

Accordingly, numerous difficulties in application can be already avoided or at least minimized by a “clean” manufacturing. A clean manufacturing of foam core sandwich structures includes amongst other the following points:

- Precise application of glue (masking the area to be glued) in its required amount and not more (latter rule applies anyway for a good glued connection).
- In case of excessive glue, immediate removal
- Leaving the peel ply as long as possible on the face sheets. This means either until two parts are glued or till the structure has been finished.

Another method which is applied at an area of bad later access is to stabilize the foam’s surface by applying a very thin, barely visible, layer of glue. However this is a method not to be preferred as it is to be considered as “excessive” glue and so a potential source of outgassing.

In addition to these points, also after the Landing Module’s manufacturing several measures were applied, which are mostly standard for any kind of spacecraft structure/part:

- Removal of last residual (cured) resin spots, if possible
- Closing the remaining open foam surface with (perforated) Kapton® tape before outbaking (see Figure 5)
- Outbaking
- Avoiding even fluids such as isopropanol, if possible

Considering the above mentioned mitigating strategies and applying an outbaking for almost 9 days at 85°C ensured that the MASCOT structure fulfils the required outgassing constraints. Adding the perforated Kapton® tape on the open foam avoids flaking during further handling and during dynamic loading during launch, but allowed chemical residuals to outgas during outbaking.

III. LESSONS LEARNED

Summarizing the manufacturing of the MASCOT Landing Module, some lessons are learned and will influence the design of potential future MASCOT derivatives. But not only for derivatives, also for CFRP-foam sandwich constructions in general are these points worth to mention.

One major point is how to apply an “open” foam sandwich in a spacecraft structure. Because of the mentioned drawbacks, foam is typically used in completely “wrapped” or closed designs, i.e. no foam is exposed. MASCOT has proofed that, at least for a small structure, partially exposed foam – later covered with perforated Kapton® tape – can be applied. Also closing the foam with an additional L-shape ply, which may be required for optical reasons, turned out to be an adequate and lightweight protection of the foam against further abrasion or loss of residual flake particles generated during cutting. Therefor one L-shaped ply is sufficient enough and does not increase the mass of the structure significantly. In case of MASCOT, for example, closing all remaining exposed foam surfaces, with one CFRP ply instead of Kapton® would have resulted in an additional mass of only 25g. The additional manufacturing time can be assumed to be the same as a later taping of the open foam surfaces with Kapton®. However an outbaking is still necessary, as molecules will escape through remaining “gaps” under vacuum and/or high temperature conditions.

Not less important, especially for MASCOT derivatives, is the fact that the current design can be realized in parts only because of the similar dimensions of the mounted P/L (MicrOmega & MASCam) and the interfacing structure. This allows a load introduction and redirection close to edges to adjacent normal-orientated walls. Hence, a scaling of the structure with same instrument sizes is not straight forward. This will require a concurrent scaling of the instruments or at least of their footprints. Alternatively an additional or newly designed (Middle) Wall and Bottom Plate must be considered to provide additional mounting options. Both will influence the structure, which is built in a high degree around the current instruments’ designs and sizes.

In terms of lightweight design the currently applied solid CFRP inserts to fix the radiator and as depicted in Figure 4 are not lighter than a comparable aluminium design. The solid CFRP insert design sums up to 1.56g per connection, which includes the CFRP block (0.49g), a Titanium nut with a corresponding hat-shaped fixture (0.4g) and a Titanium screw M3x19 (0.67g). In contrast a threaded aluminium insert design weighs only 1.43g including a shorter screw (M3x16; 0.63g). A nut is no longer necessary and so the screw doesn’t have to go through the insert. A second alternative for the Radiator I/F design are threaded solid CFRP or resin blocks with Helicoil® insert. This may bring down the I/F mass to approximately 0.8g, but will require additional mechanical tests regarding pull out strength.

Another lesson was learned is the preparation for mechanical tests and installing the required accelerometers. During STM testing only mass dummies without harness, multi-layer insulation et cetera were present. But for EQM and FM configuration the structure has so little space left, that it was very difficult to install inside the structure accelerometers with superglue. Therefore first a Kapton® stripe is taped on the actual surface where the sensor is supposed to be placed. Then the glue is applied on the sensor and the sensor is put with tweezer and in correct alignment in place – all this without contaminating any instrument or surface in the way. Consequently, not every try to glue a sensor resulted in a firm contact. Similarly, removing the Kapton® tape with the glue residual after the test is not much easier. In order to simplify this process it is in future considered and recommended to have dedicated inserts and interfaces for threaded accelerometers when a system is so small and highly integrated, but still complex enough to require additional sensors inside. These connections can be used multiple times, ensure firm connection and no glue or wax can contaminate anything inside.

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