# Development of an Additive Manufactured Mass, Volume and Cost Optimised Ti-6AL-4V Fuel Tank for Microsatellite Propulsion Systems MiniTANK

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**There is a growing market need for nano and microsatellite propulsion systems to dramatically expand satellite mission capabilities, extend orbital life and decrease the cost of constellation deployment. This paper presents the development of a novel custom-designed cuboidal fuel tank, optimised for mass and volume utilization ratio to be used in conjunction with a new miniaturised microwave electrothermal thruster. The thruster is based on anhydrous ammonia fuel, and requires a maximised fuel tank to increase operational capability over conventional tank designs. MiniTANK is a lightweight fuel tank that can only be manufactured through Additive Manufacturing (AM). It applies a generative design approach to define an optimised topological structure for further development into a viable AM model. This model features, a novel internal structural lattice to maximize the stored propellant volume within a given envelope for a minimal tank mass; a lightweight support structure; and fluid wicking features to promote flow in micro-gravity. Design for AM processes was employed to refine the existing geometry and create a self-supporting structure, negating requirements for internal support structures and hence cleaning. The application of generative design/optimisation software, advanced CAD, FE analysis and AM process simulation, has facilitated the design of a fuel tank that meets all the stiffness and mass criteria, whilst also being internally self-supporting. The final design is a cuboidal fuel tank with a 90% volume utilisation ratio, compared to ~60% for currently used spherical/cylindrical tanks. A mass reduction of 28% compared to a simple thick-walled cuboidal tank has been achieved (~ 360 g from 500 g). Pressure testing results displayed that the fuel tank ruptured at 74 bar ($\boldsymbol{7.4x10^6 Pa}$), which is 1.9 times the safety factor of the design burst pressure specified in ECSS-E-ST-32-02C REV 1 standard.**

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# I.Introduction

MiniTANK was a program of work developing mass optimised fuel tanks for Nano and micro-satellite propulsion systems. These fuel tanks are part of a larger ecosystem of light-weight next-generation CubeSat systems, which provide extended LEO mission capabilities and a reduction in the cost of constellation deployment. Fuel tanks are of interest as they are one of the heaviest components of a CubeSat, weighing ≥ 500 g [1]. The MiniTANK project was an exploration of the bounds of the possible in Design for Additive Manufacture (DfAM) for space propulsion applications. Using Finite Element Analysis (FEA) optimisation techniques, alongside DfAM approaches, the research consortium, supported by UKSA NSTP Pathfinder funding, has developed a lightweight solution against a CubeSat fuel tank design specification.

Existing fuel tanks either use volume-inefficient but structurally strong cylindrical and spherical forms, or volume efficient cuboidal tanks with thick walls and high mass for structural strength [2]. The CubeSat propulsion system relies on fuel tanks which are filled with either a compressed liquid or a gaseous propellant to generate thrust [3]. The thrust generated is directionally proportional to the pressure of the propellant within the fuel tank [3]. The pressure decreases within the fuel tank (due to propellant usage), this also decreases the maximum thrust of the propulsion system [3]. Therefore, CubeSat fuel tanks must be able to withstand high pressures (~ $3.9x10^6 Pa$) and are often limited in design when using conventional manufacturing techniques. Fuel tanks are manufactured using variable length titanium sheets which are formed into spherical rings. Combined with hemispherical domes, these rings then undergo a combination of processes such as, forging, heat treatment, machining and welding in order to achieve the final form [4]. Using conventional processes, targeted mass reduction cannot be achieved, as complex designs are either unfeasible or uneconomical for manufacture. Fuel tanks that are manufactured using traditional methods waste approximately 80% of the sourced material [5,6]. Due to this, fuel tanks incur high manufacturing costs and lengthy production lead-times.

In order to achieve the design freedom to manufacture optimised fuel tanks economically, AM is increasingly being adopted for the development of next-generation CubeSat systems. Using AM, it is possible to integrate functionality directly into the part, this was demonstrated by Teng and Jin [2] who developed a 3D metal printed fuel tank in Ti-6Al-4V which included an internal mesh structure [2]. This fuel tank was rectangular in shape to provide an increase in fuel storage and the mesh structure was for reinforcement of thin walls [2]. The design was able to achieve an improvement in compressive stress by 58.71%, a volume utilisation increase of 24.52% and a mass reduction of 11.67% when compared to a conventional storage tank [2]. A further study undertaken by Solorzano [7] used an AlSi10Mg 3D printed fuel tank, which was structurally tested to withstand launch and on-orbit environments [7]. The fuel tank was designed with an internal stiffening structure that acted as integral supports to aid the printing process [7]. The test results showed that the fuel tank was able to achieve 2.5 times the operating pressure, which closely aligned with the Factor of Safety (FoS) of 2.1 predicted using FEA [7].

Prior work demonstrates the validity of AM as an alternative route for manufacturing fuel tanks. Through recent advancements in DfAM software, it is now possible to further lightweight fuel tank designs whilst maintaining overall structural integrity. As discussed, Teng and Jin [2] created a fuel tank design, which achieved a high volume utilisation of ~87.7% and low compressive stresses <172 MPa [2]. This, however, was at a compromise in weight as the internal mesh was not optimised in design and contributed to the final tank mass of 530 g [2]. In comparison, a conventional fuel tank prior to installation is ~368 g in mass, after assembly this increases to ~600 g [2]. The 3D printed rectangular fuel tank did not require any reinforcement that would incur additional weight, but was only able to achieve a small weight reduction of 70 g. In contrast, Solorzano's [7] study focused purely on meeting the structural performance and material properties of a conventionally manufactured tank [7]. The study showed that a 3D printed fuel tank in AlSi10Mg exceeded the performance of wrought Al6061 T-6, and during pressure testing was able to withstand rupture up to 28 bar ($2.8x10^6\ Pa$) [7]. The fuel tank was designed to withstand the maximum operating pressure of ~11 bar ($1.1x10^6\ Pa$), which implied that the design was over engineered and could be optimised [7]. From a manufacturing perspective, the chosen metal AM process (SLM) resulted in a build time of 135 hours [7]. A build time of this magnitude would be cost prohibitive, as typical industry machine rates are estimated at ~£80 per/hour [8]. This would equate to a build cost of £10,800 per build for two fuel tanks excluding any additional value added processes. When compared to conventional manufacturing methods this is a significant increase in cost.

The MiniTANK design, was an extension of this research and through the use topology optimisation software, a balance between a lightweight yet structurally strong 3U CubeSat fuel tank was found. Using topology optimisation and designing for the metal AM process, material was removed from areas of low stress and optimised for the pressure conditions applied and the selected material (Ti-6Al-4V). This approach provided a logical placement of material and allowed for a significant reduction in weight. The fuel tank design made use of an internal stiffening structure with a secondary function to support the transport of propellant. With the ability to remove unnecessary material and supports, this had a positive impact on the total build time through a reduction in laser scanning. The final print of a single fuel tank using a Renishaw AM SLM system was ~15.5 hours.

## II.Process Selection

Metal additive manufacturing (AM) was the process adopted to build the fuel tank prototypes. MiniTANK used Laser Powder Bed Fusion (LPBF) for fuel tank manufacture; where a fibre laser is used to impart thermal energy selectively to fuse regions of fine metallic particles, in order to form a Near Net Shape (NNS) component [9]. This is also known as Selective Laser Melting (SLM) and is capable of creating highly complex geometries with features not possible through subtractive manufacturing processes.

## III.Product Design Requirements

The specification of the MiniTANK design was a product that maximised the internal tank volume, whilst minimising mass via the application of novel internal structures. The fuel tank would also consider the application of propellant management devices to promote fuel wicking, for example; vanes, meshes, and sponges.

The technical requirements of the proposed fuel tank are summarised as follows:

- The fuel tank must feature a single propellant line based on a titanium tube. This will be mounted centrally in the large face of the fuel tank.
- It will fit within a cross-section of 96 x 96 mm and a length of ~78 mm in the default configuration and will contain mounting points compatible with a CubeSat frame.
- The target propellant volume to be contained is 0.6 litres.
- The dry mass of the fuel tank must be less than 500 g and target 374 g.
- The fuel tank must withstand a pressure of 39 bar at a 1.5 safety factor over the expected maximum fuel vapour pressure of 26 bar, using the method defined in ECSS-E-ST-32-02C REV 1 [10].
- The fuel tank must be suitable for operation between 0 °C and 60 °C.
- The design will provide a ~90 % volume utilisation ratio, compared to ~60 % for currently used spherical/cylindrical fuel tanks.
- Mass reduction is expected to be ~20 % compared to a simple thick-walled cuboidal fuel tank.

## IV.Methodology

Creating a high performance AM product requires the successful intersection of process knowledge, process simulation, topology optimisation, and CAD modelling, Figure 1. Currently, these activities are integrated by the AM design engineer, as the software packages used operate independently of one another. This inherent complexity is a key feature of topology optimisation driven DfAM activities. Associated workflows are non-linear due to the differing capabilities of software required for the core activities of the process. This leads to a high software burden for successful DfAM applications.

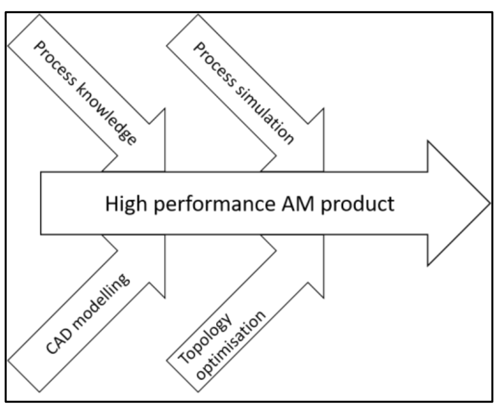


**Figure 1 - Example design process flow for the manufacture of high performance AM products.**

The output of a topology optimisation process is often visually complex and unsuitable for immediate manufacturing, Figure 2, this requires additional refinement in CAD. When this is combined with an advanced manufacturing process, such as metal AM, the software burden is further increased. This is the result of the AM systems requiring independent FEA, build simulation, and model slicing in order to translate the created geometry onto the AM machine. An example of this complex software workflow is shown in Figure 3, below.

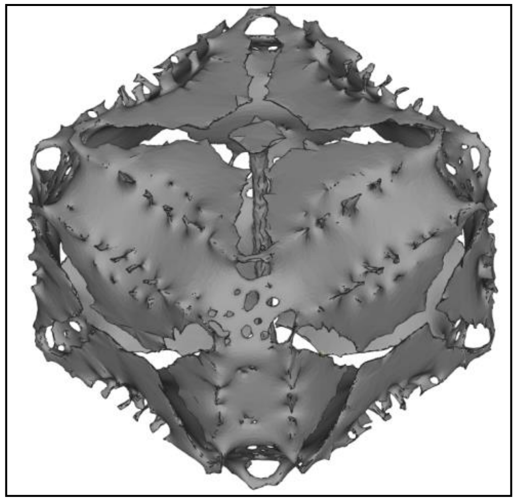

**Figure 2 - Topology optimised output of a lightweight stiffening structure concept considered for fuel tank integration.**

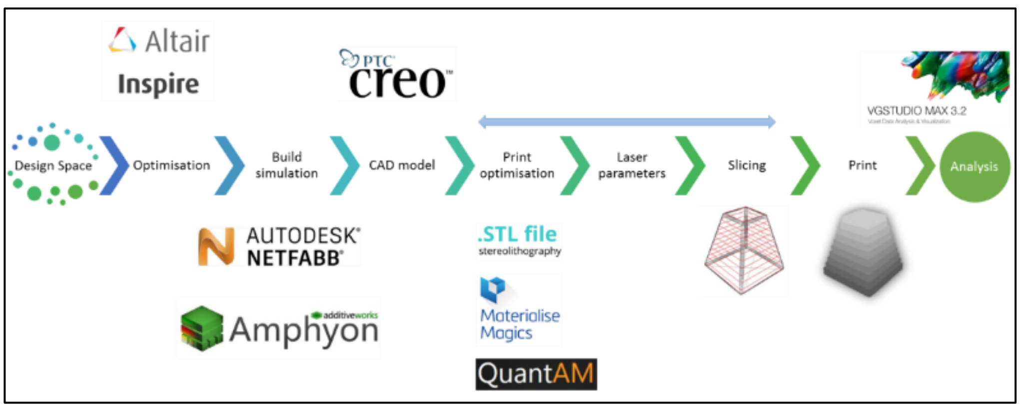


**Figure 3 - An example end to end software workflow of a metallic AM component from initial design to analysis.**

This paper focusses on the workflow required for viable AM geometries, and their subsequent performance testing. We do not consider the build simulation aspects of the programme of work or the methods applied in the physical builds themselves, as they are not relevant to the discussion.

## V.Topology Optimisation Process

Topology optimisation techniques require the definition of a design space, within which material can be manipulated in order to create an optimised structure. The design space is defined by the dimensional envelope, applied pressure, fixing points, and simulation objectives. The simulation objectives for this application were either to achieve the maximum stiffness or a minimum mass solution.

The candidate material for the fuel tank was Ti-6Al-4V grade 23 powder, which is compatible with the selected metal AM process. This powder is a higher purity variant of existing compositions of Titanium and provides an increase in both ductility and fracture toughness [11]. This material also has a balance of strength (UTS >900MPa Heat Treated) to weight (density 4.42 g/cm$^3$) properties, making it ideal for lightweight load-bearing structures [11]. A target during the simulation was to ensure that using this material all stresses were kept below the Yield Strength (YT) of ~900 MPa.

To reduce the computational burden for simulations and simplify the model, the fuel tank was segmented to one quarter of its volume and analysed using mirror constraints. This section was used to define the fixed and movable regions of the geometry. The outer shell was defined as non-design space at 1.5 mm thickness and hence fixed, with the bulk volume internal as design space and available for manipulation in response to the applied loads. The maximum operating pressure of 39 bar (including a safety factor of 1.5) was uniformly applied to all internal surfaces of the section.

Once these conditions were set, the topology optimisation was run in Altair Inspire. This uses a mathematical method to determine the optimum material allocation within a design space. The output generated from the design space is defined by the loads, boundary conditions and constraints imposed. Therefore, based on the start geometry and end application, the topology optimisation can be modified to generate a wide variety of complex designs. The final output of the topology optimisation requires smoothing to create a solid body as elements may be missing and structures incomplete. Figure 4 shows the flow of the topology optimisation from setting of the design space to smoothed output. Table 1 defines the primary settings used within Altair Inspire in order to generate the topological optimisation.

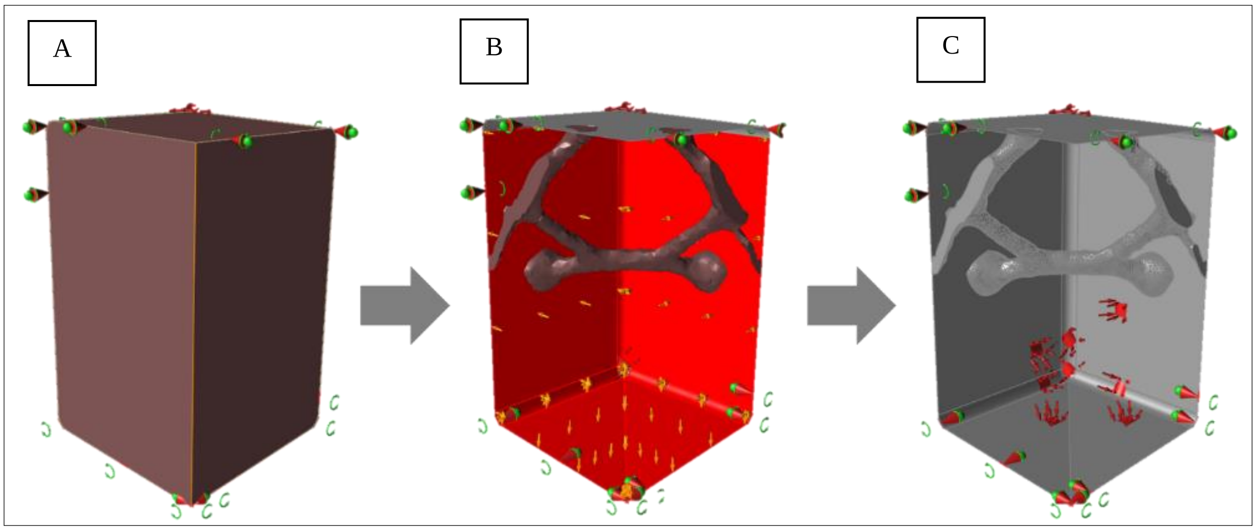


**Figure 4 - Topology optimisation flow from left to right, A: initial quarter volume for analysis with rigid points and internal pressure applied; B: initial output from software creating suggested geometry; and, C: final smoothed geometry to remove missing elements.**

**Table 1 - Altair Inspire topology optimisation parameters.**

| **Altair Inspire topology optimisation setup** | | |
|---|---|---|
| Objective: | Maximum stiffness | Unit |
| Mass target of 1/4 section fuel tank: | 0.0875 | Kg |
| Frequency constraints: | None | - |
| Thickness constraint: | 3 | mm |
| Speed / accuracy setting: | Faster | - |
| Contacts: | Sliding only | - |
| Gravity constraints: | No | - |
| Pressure (internal faces) | 3.9 | MPa |

The topology optimisation process suggested a stiffening geometry to resolve anticipated distortion. Figure 5 presents a von Mises plot of the topology optimisation output, highlighting that further reinforcing elements were required for stiffening the fuel tank walls, particularly on the bottom face of the tank.

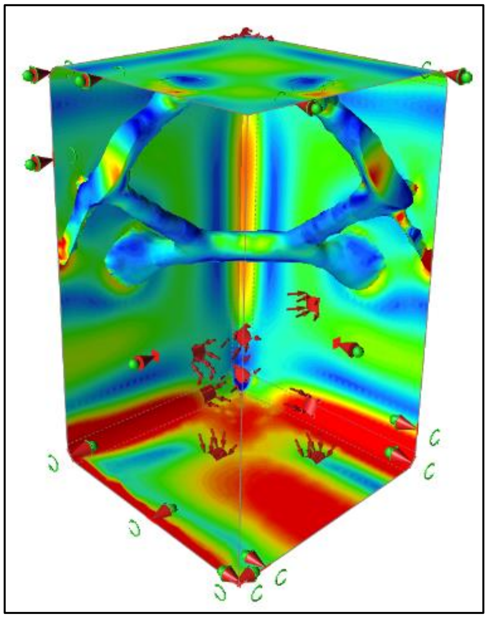

**Figure 5 - Von Mises stress profile of the modified maximum stiffness topology optimised output.**

Smoothing of the beam elements created by the Altair Inspire topology optimisation process can be achieved with the included PolyNURBS surfacing tools. This is time consuming as it requires manual form-fitting of surfaces and requires several iterations to achieve a surface suitable for printing. It is also not sensitive to the requirements of the AM process, being unable to factor a build angle in its settings. As an alternative, the raw output was converted to an STL CAD model and imported into PTC Creo. The STL model was then used as a reference for solid modelling of the fuel tank design.

A quarter section of the fuel tank was modelled in PTC Creo using the topology optimised output generated in Altair Inspire. Additional stiffening beams were created and also wicking veins were introduced inside the tank. Due to these additional features, and trialling a solid skin thickness from 0.5 to 1.5 mm, FEA was iteratively performed in Altair Inspire following edits made in PTC Creo. Each time a design change was applied, additional checks were required to ensure the stress limits, displacement, and manufacturing constraints were being satisfied.

The fuel tank design was iterated multiple times through the described fragmented software workflow, this included the use of PTC Creo, Altair Inspire, Netfabb simulation, Additive Works Amphyon, and Materialise Magics to achieve a viable output. Whilst this represents a complex workflow, it was essential to move between software packages as each provides a unique function required for the design of the part. FEA iterations are shown in Figure 6, highlighting how the stress profile was improved with each iteration as a solution was moved towards.

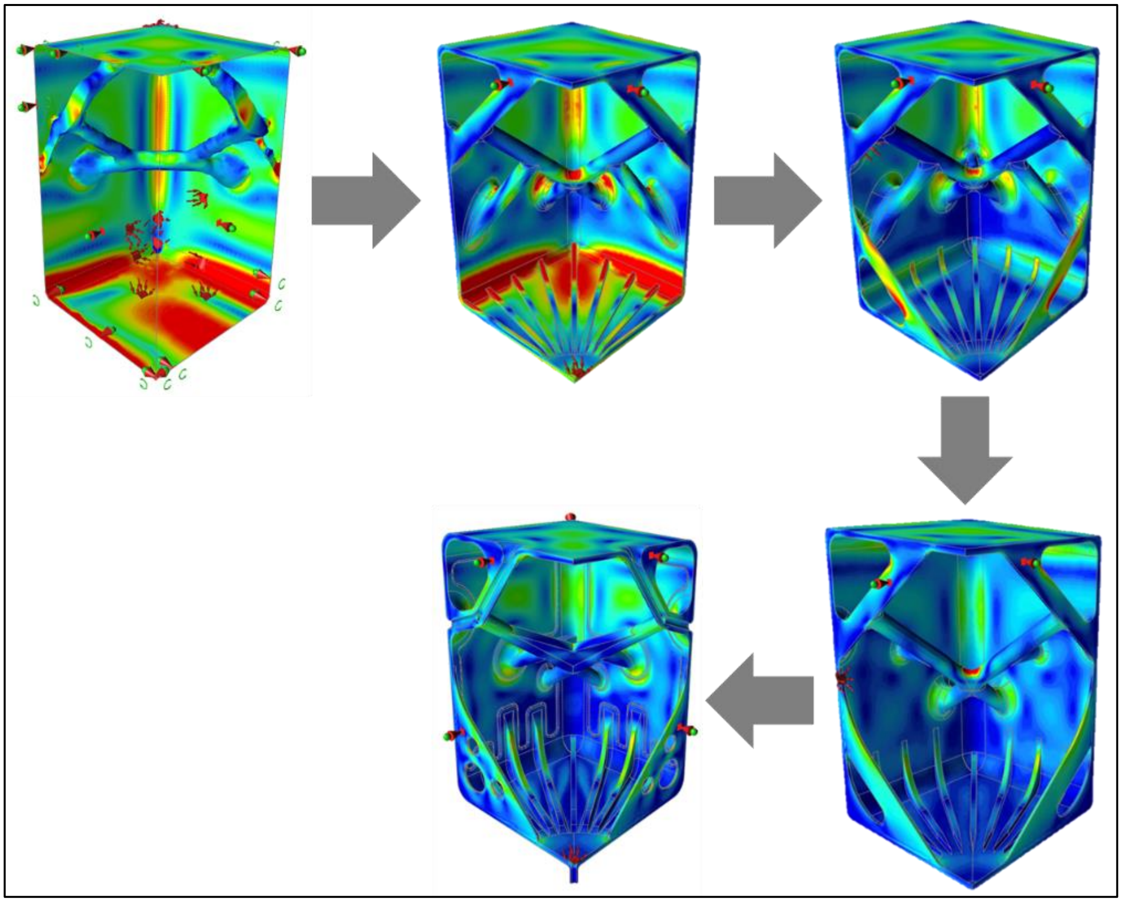

**Figure 6 – Iterative design cycle of a quarter section fuel tank from an initial high stress model to a refined output which includes wicking features and conformity to the self-support angle of the metal AM process.**

Figure 7 and Table 2 shows the typical set-up for FEA adopted throughout the course of this project. Quarter symmetries were again used to minimise computational burden, with pressures applied universally to the internal surfaces of the fuel tank geometry.

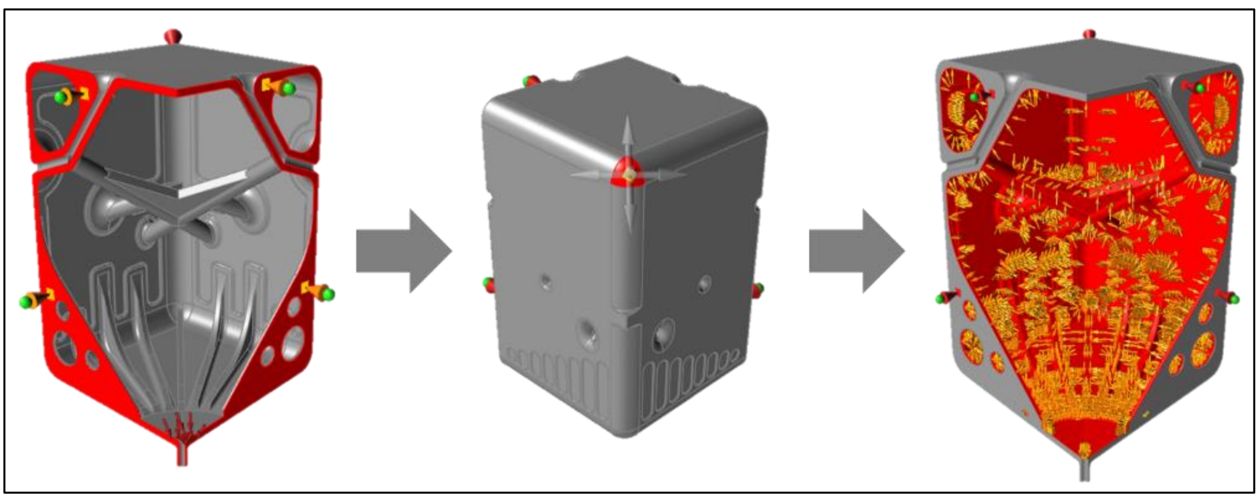

**Figure 7 - FEA model setup within Altair Inspire displaying fixing points and applied internal pressure on a ¼ section of the fuel tank.**

Table 2 - FEA parameters used on the sectioned fuel tank to simulate stress and displacement plots.

| FEA variables | Setting | Units/details |
|---|---|---|
| Pressure (Internal surfaces): | 3.9 | MPa |
| Internal rigid supports to fixate 1/4 section: | 4 | restriced in Z axis movements on given selection plane |
| External rigid support to represent bolt connection: | 1 | The bolt connection is used to connect the fuel tank onto the CubeSat frame. |
| Material Properties: | | |
| Grade: | Ti6Al4V | Titanium alloy |
| Youngs modulus: | 1.17E+11 | Pa |
| Poissons ratio: | 0.31 | |
| Density: | 4.43E+03 | kg/m^3 |
| Yield stress: | 8.27E+08 | Pa |
| Coefficient of thermal expansion: | 8.82E-06 | K |
| Mass: | 0.090491 | kg |
| Mass moment of Inertia | | |
| Ixx | 0.00017643 | kg*m2 |
| Iyy | 8.02E-05 | kg*m2 |
| Izz | 0.00017655 | kg*m2 |
| Ixy | -8.40E-07 | kg*m2 |
| Ixz | -7.41E-06 | kg*m2 |
| Iyz | 8.36E-07 | kg*m2 |
| Volume: | 2.04E-05 | m^3 |
| Mesh settings | | |
| Miniumum element size: | 0.00020602 | m |
| Global/average element size: | 0.0010301 | m |
| Optimisation settings | | |
| Miniumum thickness: | 0.0031933 | m |
| Maximum thickness: | 0.0063867 | m |
| Minimum gap: | 0.0063867 | m |

The internal features of the fuel tank, which are required for maximising strength to mass performance, have a series of associated build requirements. These requirements are driven by the inaccessibility of the internal structure of the fuel tank post build. To maximise the benefits of an AM process, it is preferable to build the tank in a single piece, thus minimising the requirement for joining multiple components in further operations post build.

Topology optimisation creates surfaces that are visibly rough, and the initial output from the Altair Inspire software shows a significantly uneven surface. This surface will be replicated and accentuated by the AM build process, which could lead to stress raisers being generated on the internal support structure. In addition to potential problems associated with surface roughness, any structures that lay below the self-supporting angle of the process will require support material to successfully build. The support material cannot be adequately removed from the closed fuel tank body post build and is therefore undesirable.

Internal structures of the fuel tank must, therefore, be self-supporting and as smooth as possible in their design. This is not currently achievable in the optimisation software applied, and has to be done using tacit knowledge of the AM build process. Figure 8 shows the obvious difference in the topology optimised structure as features are adjusted to sit within the self-supporting range of angles dictated by the process. A smoothing of the structure can be seen as well as an apparent change in the angles of the some of the structure. This was in order to link the features back to the body of the tank and the build substrate and ensure they required no additional support material.

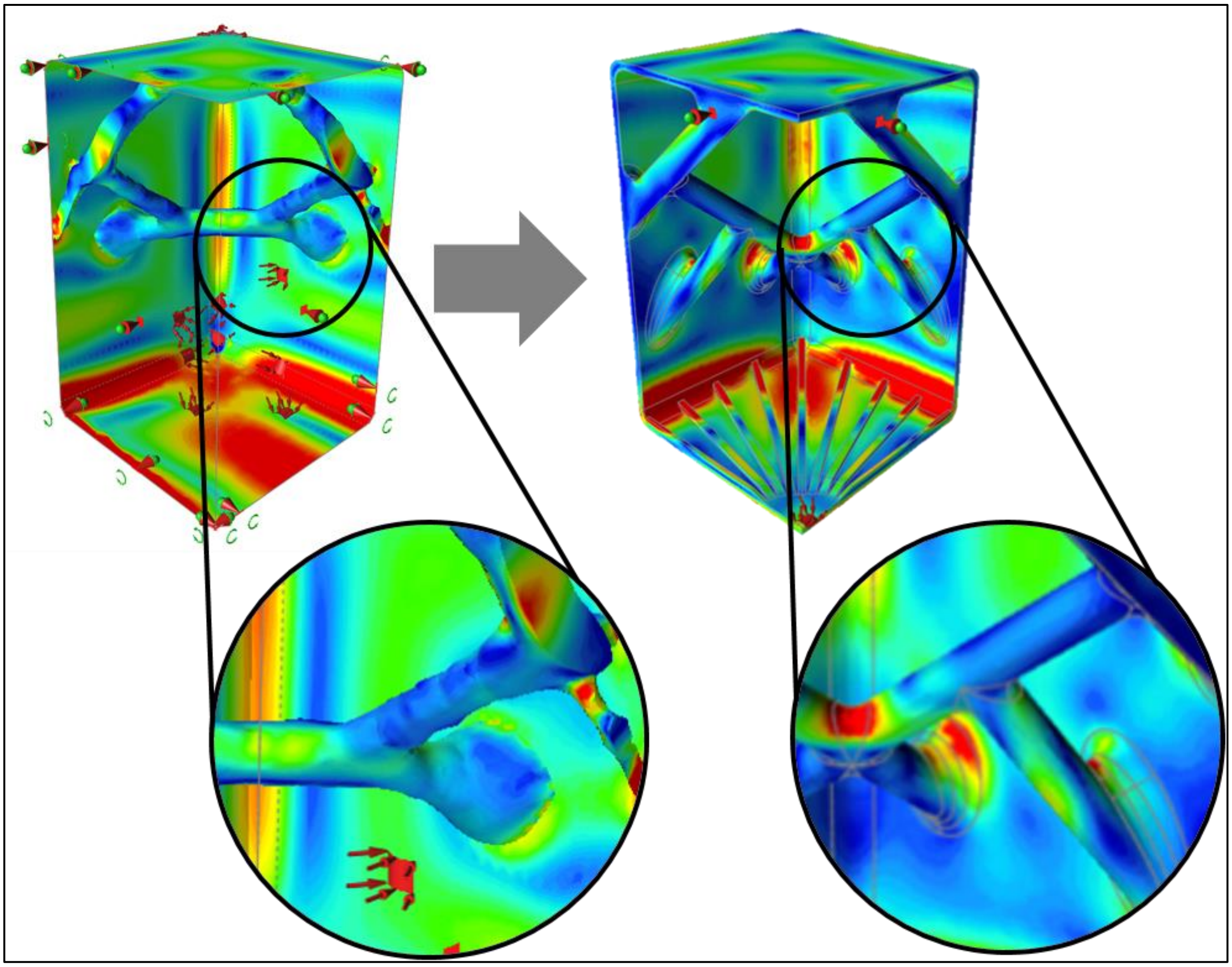

**Figure 8 - Example of topology optimised output (left) modified (right) to suit the manufacturing constraints of the metal AM process.**

## VI. Variable Skin Thickness Optimisation

Light-weighting of non-structural regions of the fuel tank surface was highlighted as a possibility on review of the FEA data, Figure 9 left. Low stress regions of the fuel tank skin where thinning may be viable were apparent, and an opportunity recognised for the support structures to be hollow and open to the tank surface. These factors would further reduce mass of the tank, without sacrificing the structural performance. Again the fragmented software workflow needs to be considered at this point. The simplest route to creation of a variable skin thickness was not necessarily the most intuitive with respect to the software available.

A stress profile of the complete tank was created in Altair Inspire. This was incompatible with the modelling software and would not allow data to be transferred over to automate the material removal process. A greyscale map was generated and used to guide the removal of material, Figure 9 centre. By varying the wall thickness between 0.75 mm and 1.5 mm, and reconfiguring the internal support structure as 1.5 mm wall thickness tubes, a revised structure was created, Figure 9 right.

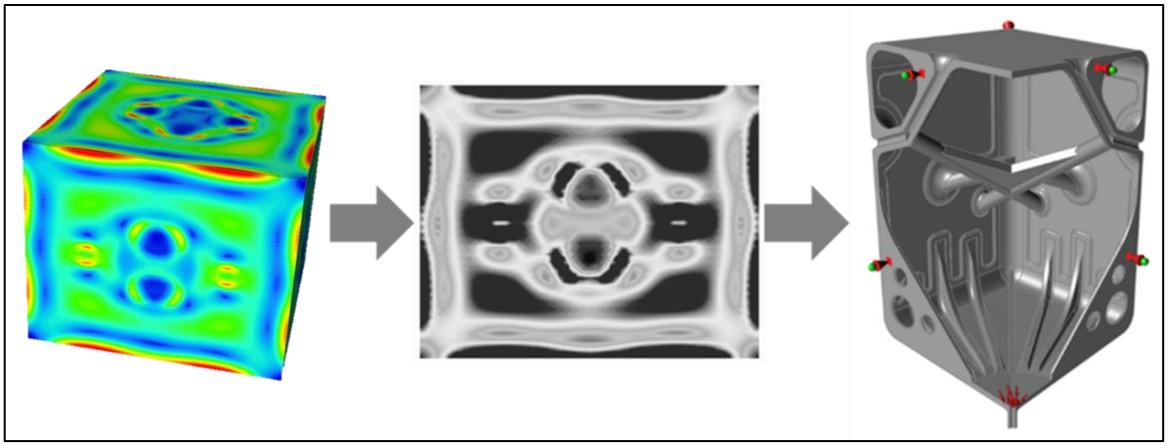

**Figure 9 - Image left displays a stress plot of the full fuel tank, green regions are low stress regions, centre image is a 2D greyscale map created in Adobe Photoshop which was used to assign variable thickness constraints, image right is a section of the fuel tank developed in-line with the manufacturing constraints of the metal AM process and also used for final FEA simulations.**

Following FEA, no other high-stress zones were predicted in the final design. Displacement simulations exhibited a maximum displacement of <0.5 mm in the worst affected zones, an example is shown in Figure 10.

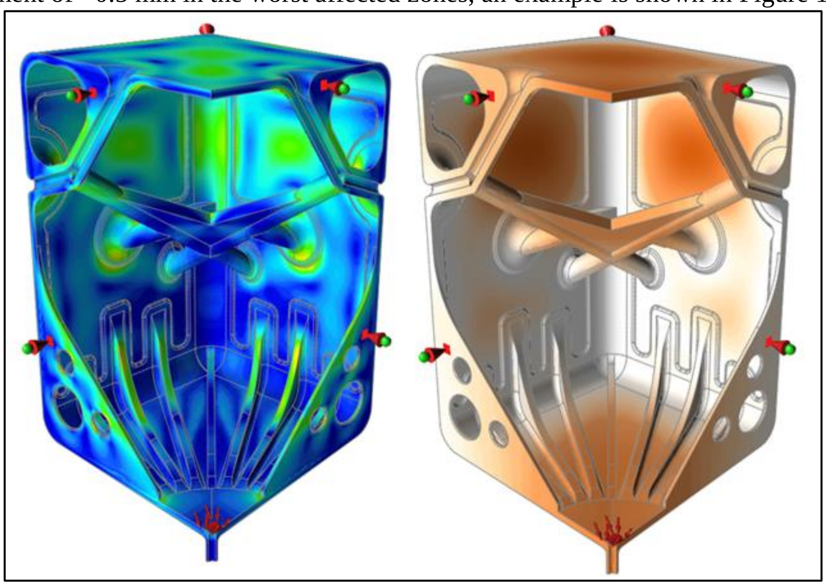

**Figure 10 - Von Mises stress plot left of final fuel tank structure displaying no high stress zones, right is an image of the displacement result with orange regions the worst affected areas <0.5 mm variance.**

The final geometry was generated by mirroring the quarter model about the centre axis, Figure 11. this created a near final geometry ready for simulation in Altair Inspire, Netfabb and Amphyon for build. The design workflow adopted an approach that required a number of software packages in order to verify each design change. This was to ensure that small changes were made without creating unnecessary work in full re-design. The final design created a solution which provided maximum stiffness in the lightest possible form. Modelling in PTC Creo provided design control of the stiffening structure to ensure compatibility with the printing process. All features were modelled to self-support at a 30° overhang and without sharp geometry transitions.

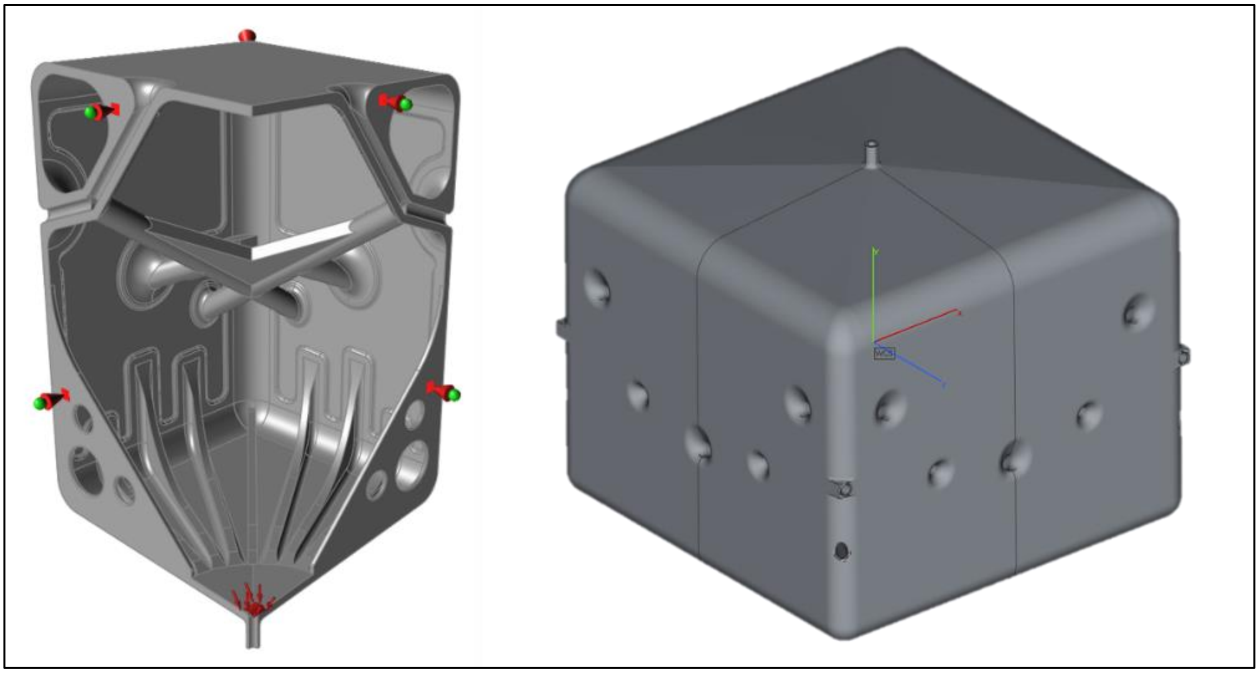

**Figure 11 - Optimised 1/4 section of the fuel tank left which was mirrored about the centre axis in order to generate the full geometry.**

## VII.Pre-build simulation

Following structural FEA, process simulations in Additive Works Amphyon were undertaken. This was in order to highlight any areas that required design modification prior to part printing. Predicted stresses in the fuel tank were relatively low due to the design consisting of thin wall structures and a low cross-sectional slice per layer in the Z-axis. High displacements, particularly due to the thin wall nature of the fuel tank, were evident in some of the sidewalls, Figure 12 & Figure 13. These areas were influenced by the internal stiffening structure constricting movement, and some residual stress build-up due to the variable thermal conditions created.

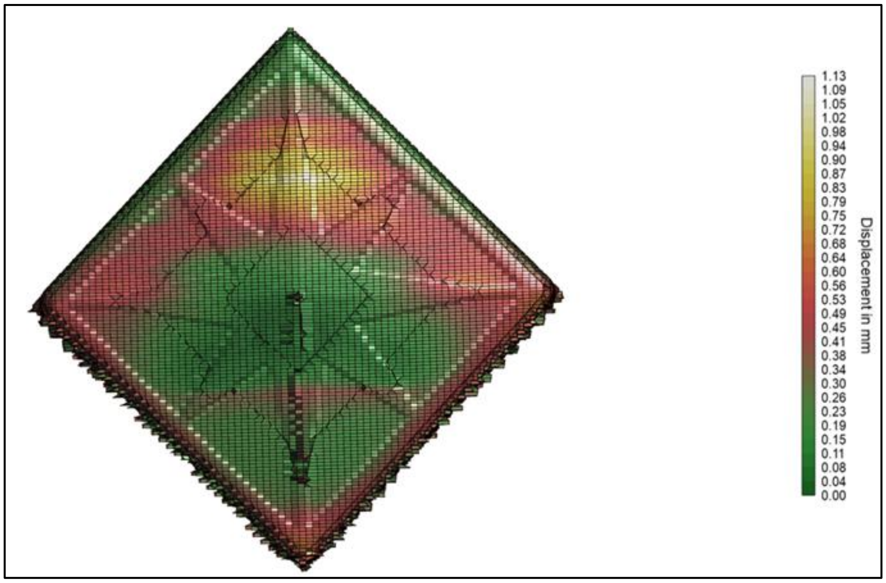


**Figure 12 - Optimised fuel tank displacement plot view 1.**

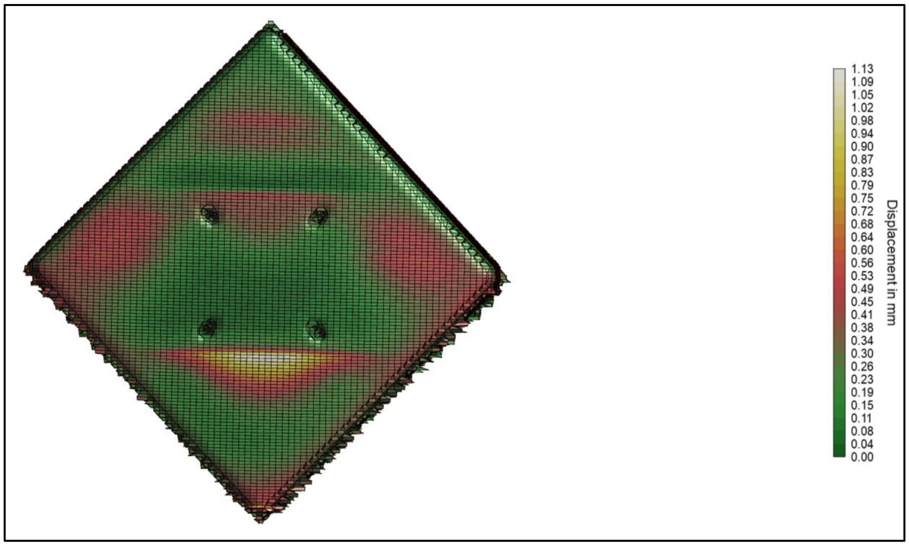


**Figure 13 - Optimised fuel tank displacement plot view 2.**

## VIII. 3D printing

The fuel tank was imported into Materialise Magics for final support application. External supports were applied to all down-facing regions that required attachment to the base plate. The main supports applied were in the form of block supports modified into thin walls with a thickness of 0.5 mm. The thin wall supports connected onto the part using teeth connections to aid in removal post-build. Additional tree or beam supports were applied to specific side wall locations in order to counteract the high displacement zones predicted in process simulations, see Figure 14.

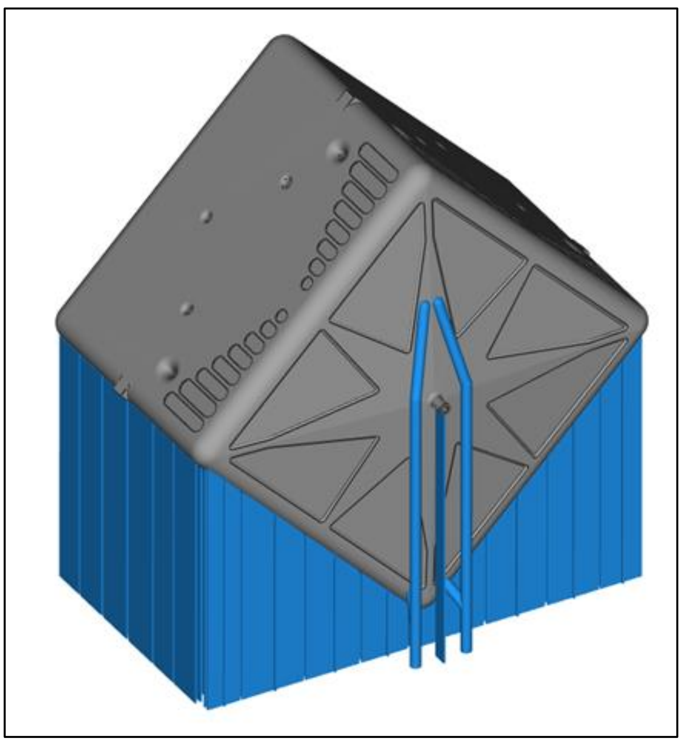

**Figure 14 - Fuel tank with external supports applied (blue) view 1 - star imprint on outlet face applied to remove material in low stressed zones.**

The machine used to manufacture the MiniTANK was a Renishaw AM250 SLM system. The following is a list of specific parameters used for print:

- Layer thickness: 0.06 mm layers.
- Material: Ti6-Al-4V grade 23.
- Hatch laser settings:
    - Power: 200 W, exposure time: 70 µs, hatch distance: 0.095 mm, point distance: 0.065 mm.
- Border laser settings:
    - Power: 160 W, exposure time: 30 µs, border distance: 0.04 mm, point distance: 0.02 mm.
- Scan strategy: Chessboard with single border scan.
- Argon purge: Purity 99.998 %
- Substrate thickness: 15 mm, platform temperature on start 170 °C
- Total build time: 15 hours 45 minutes
- No. of parts: 1

## IX.Testing

The next stage of the process was to build further iterations of the fuel tank with features included to support pressure testing. The project focus was to develop a fuel tank whose design met the structural requirement to withstand the maximum fuel vapour pressure of 39 bar including an S.F. of 1.5. In order to validate the simulation results and material selection for the fuel tank, pressure testing was arranged at the AMRC's Advanced Structural Testing Centre (ASTC).

To support testing, the fuel tank was modified to include an extended boss around the outlet hole, Figure 15. Post build, the boss would be threaded to accept a 1/8" BSP Female to 1/2" BSP Female adaptor - 2553 1/8" - 1/2" fitting. A 1/2" BSP male to 3/8" NPT female adaptor - HF69 was then used to interface with the pressure test rig.

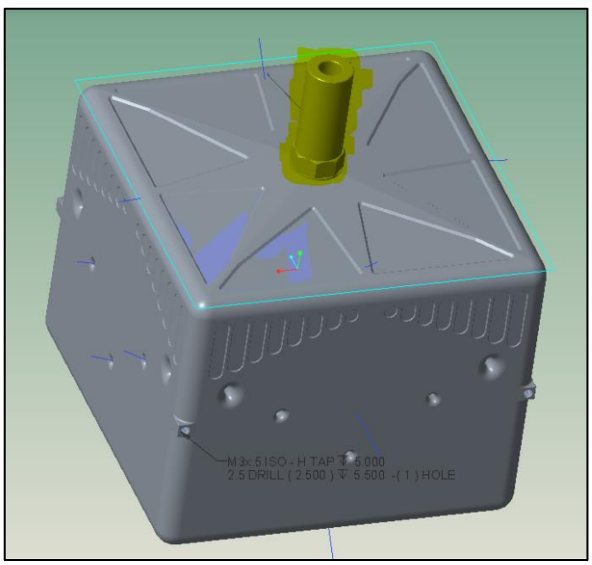


**Figure 15 - Fuel tank re-printed with an extended boss feature to support pressure line connection.**

Table 3 shows the equipment used during the experiment. All equipment was already held by the ASTC with the exception of two hydraulic adaptors, which were purchased specifically for this test, and the high speed camera. The composites group within the AMRC was able to offer a high speed camera to record footage of the pressure test.

**Table 3 - List of experimental equipment used to support pressure testing.**

| Item | Details |
|---|---|
| Female to female adaptor | 1/8" BSP to 1/2" BSP |
| Male to female adaptor | 1/2" BSP to 3/8" NPT |
| Hi Force hydraulic hose | Hi-Force HC4 |
| Hydrapack hydraulic hand pump | ASTC-F-1009-A |
| HBM Pressure transducer | P3MB #104910688 |
| Hi Force manifold block | Hi-Force HM4 |
| Hi Force pressure gauge | Hi-Force HG4 |
| Hi Force right angle gauge block | Hi-Force HF16 |
| Druck DPI digital pressure gauge | DPI-104 Ser 2972236 |
| Datalogger | HBM E0554 |
| Debris shield | Polycarbonate |
| High speed camera | Photron FASTCAM SA-X2 1080K-M1 |
| Video camera | Sony HDR-CX130E |

Figure 16 shows an overview of the experimental set up. The sample was placed on a plastic pallet on the ASTC strong floor with a four sided polycarbonate shield surrounding it. A wooden board was placed on top of, but not fastened to, the shield in order to direct debris upwards and away from observers in the event of an explosive failure. A second ring of polycarbonate and steel shielding was erected around the first to act as an additional barrier should the first shield unexpectedly fail.

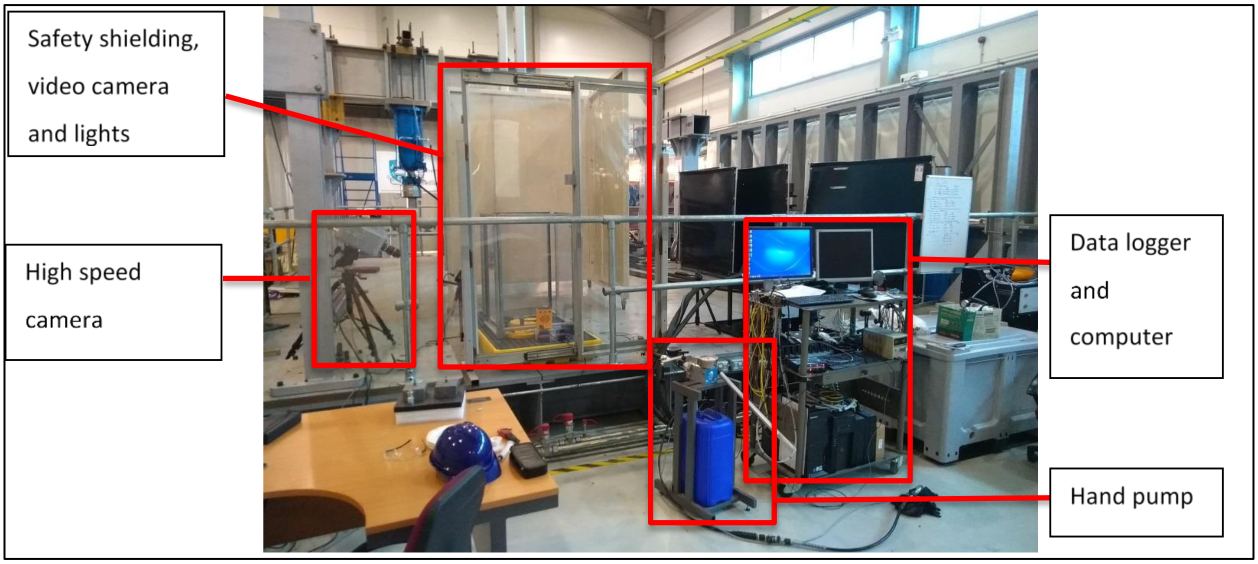


**Figure 16 - Pressure testing equipment location and set-up.**

Water was chosen as the fluid used to pressurise the tank as it is easy to handle and incompressible so unlikely to result in an explosive failure. A Hydrapack hand pump was used to pump fluid into the tank. Two adapters were fitted on to the threaded boss of the MiniTANK to allow the flexible hose to be connected. Two pressure transducers were included in the hydraulic circuit, one was positioned at the pump manifold and the other on a T-piece attached to the sample itself. Having a transducer mounted on the sample inlet enabled as accurate a reading as possible of the pressure inside the MiniTANK. Figure 17 shows the Hydrapack pump with water reservoir and manifold.

**Figure 17 - Hydrapack hydraulic hand pump and manifold.**

Data was recorded during the tests in the form of pressure readings and video of the sample under pressure. Pressure transducers were installed at two positions in the hydraulic system. A Calibrated Druck transducer was attached to the pump manifold while an HBM transducer was connected to the T-fitting between the flexible hose and adaptors that were fitted to the MiniTANK. Figure 18 shows the flexible hose (left) connected to the T-piece, with the pressure transducer (right) and attachment point of the adaptors and MiniTANK (bottom).

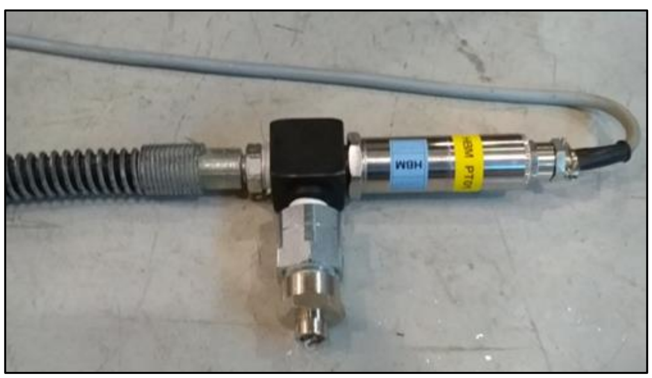


**Figure 18 - T-piece which was connected to the MiniTANK adaptors, flexible hose (left), pressure transducer (right) and attachment point (bottom).**

Two cameras were used to record the experiment, a Photron FASTCAM high speed camera and a SONY HDR-CX130E. Additional lighting was used to allow the high speed camera to capture a clear image. For final validation of the fuel tank prototype design, pressure testing was required to determine the true structural performance. The hydraulic fitting was assembled onto a single fuel tank and checked for secure attachment across the full length of the machined thread, Figure 19. ASTC then created a test plan in accordance with ECSS-E-ST-32-02C REV 1 [10] standard, which defined the pressure testing requirements.

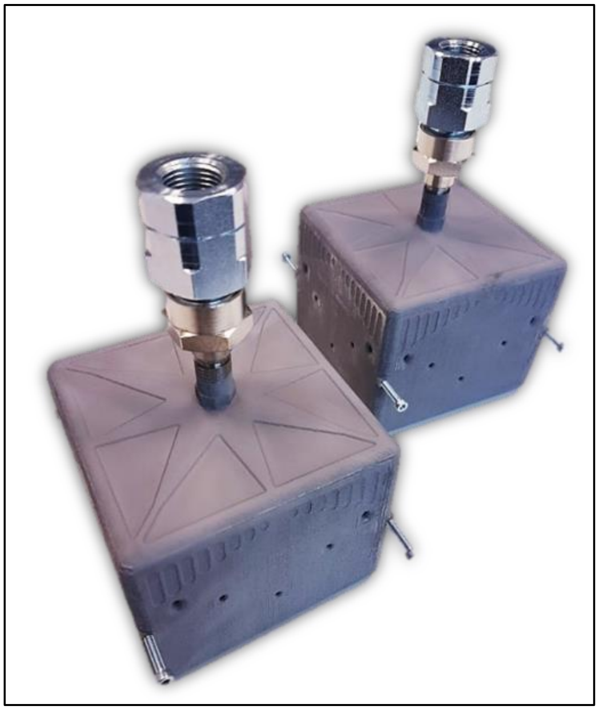

**Figure 19 - Fuel tanks fitted with hydraulic fittings ready for pressure line connection.**

Tests included an initial leak test at 39 bar, followed by a ramp-up in pressure until rupture was achieved. A proof pressure test was conducted at a pressure of 32.5 bar after which no damage to the fuel tank was visible and pressure readings remained stable. A leak test at 26 bar for 31 minutes and 40 seconds also resulted in no observable deformation or drop in internal pressure. The fuel tank withstood the design burst pressure of 39 bar without deformation and finally failed at a recorded internal pressure of 74.06 bar, giving a factor of safety of 1.90 above the failure pressure required by standard ECSS-E-ST-32-02C REV 1 [10]. Figure 20 shows tank rupture at 74.06 bar.

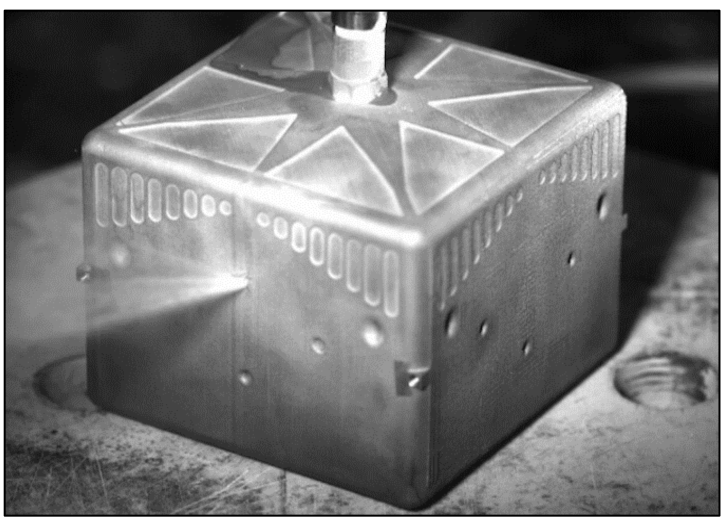

**Figure 20 - Pressure testing conducted with the fuel tank filled with water, jet stream visible at rupture point when the pressure reached 74.06 bar.**

Rupture of the fuel tank was observed in the central region of a side wall surface. Following review it was determined that this area was not supported by the stiffening structure. In addition, the wall thickness in this region was at its minimum, 0.75 mm, which would have contributed to the failure. Figure 21-Figure 23 shows the graphical output of the pressure tests conducted.

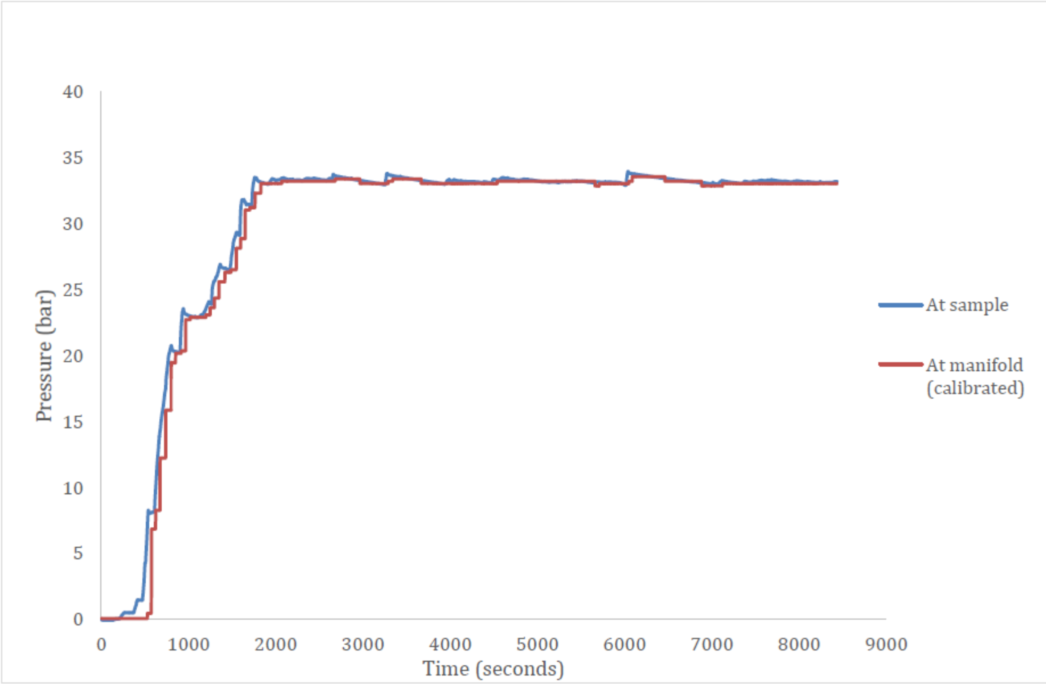


**Figure 21 - Fuel tank proof pressure test result.**

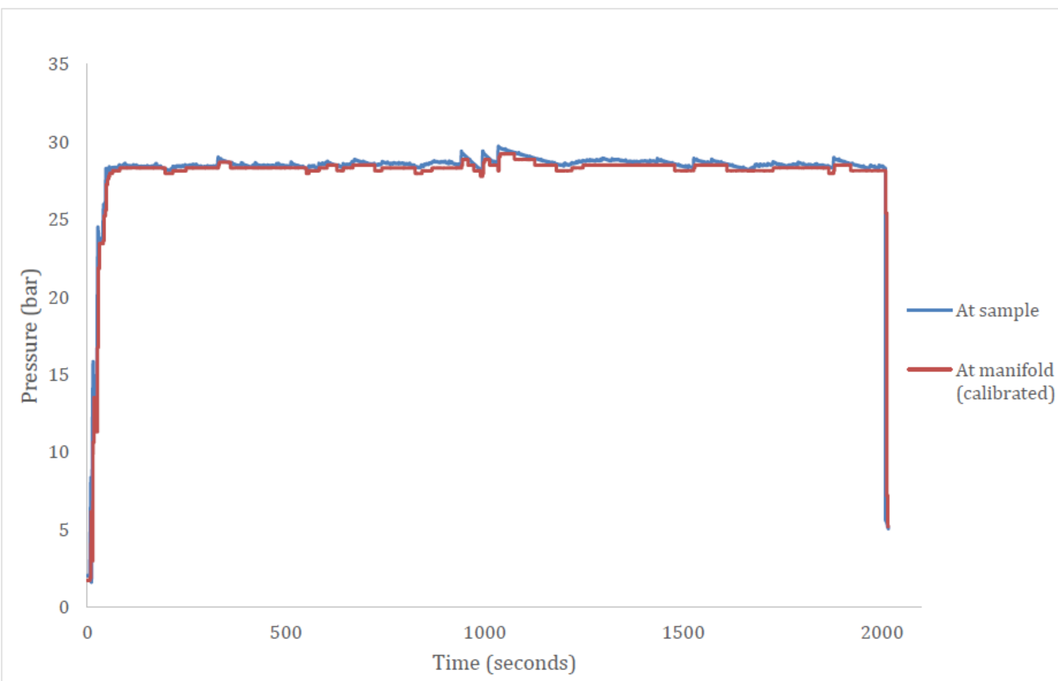


**Figure 22 - Fuel tank leak test result.**

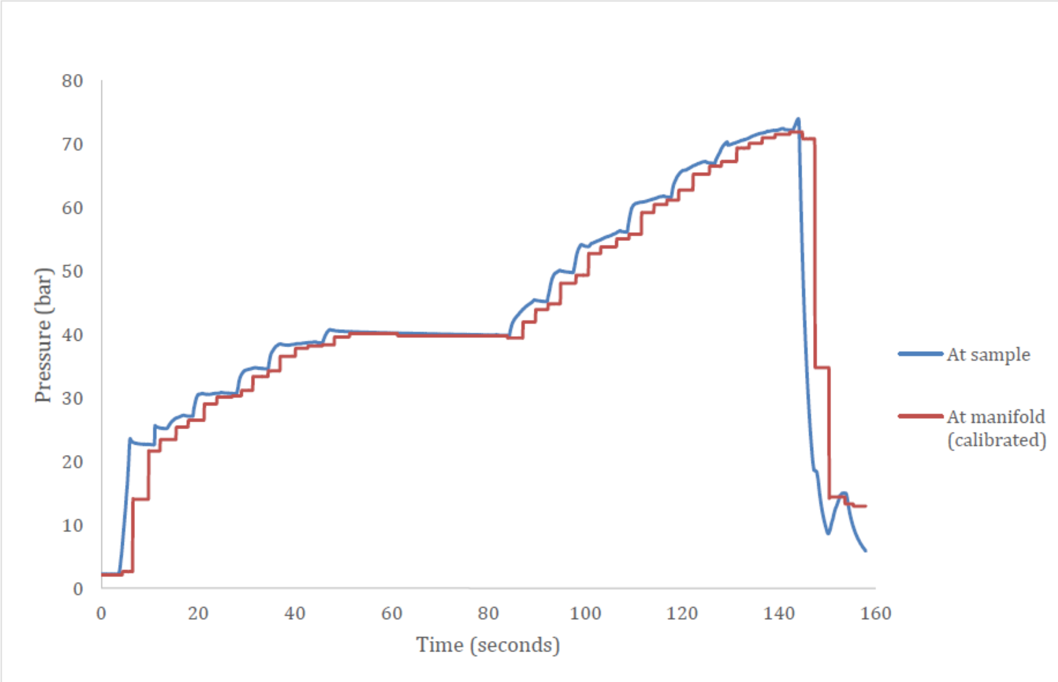


**Figure 23 - Fuel tank design and burst test result.**

Using Computed Tomography, the internal form was reconstructed and inspected without physically sectioning the fuel tank. Post pressure testing a variance of +/- 0.2 mm was observed in the stiffening structure, Figure 24. There was no evidence of cracking or separation on the major internal stiffening structure.

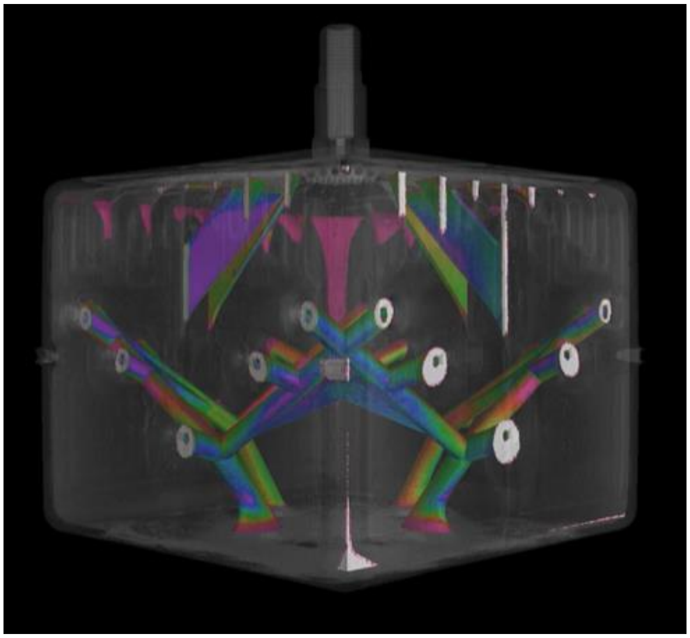

**Figure 24 - Variance analysis of the fuel tank post-pressure test.**

## X.Discussion

On review, it was possible to design a fuel tank that fulfilled the outline objectives of the MiniTANK project as defined in section III and met the testing requirements as per ECSS-E-ST-32-02C REV 1[10]. The significance of the work builds upon existing AM fuel tank designs as described in I, with an alternative approach to efficient light-weighting using topology optimisation. Previous AM CubeSat fuel tanks were found to be limited by design but still able to achieve significant performance benefits in weight, volume utilisation, and an improvement in compressive stress [2]. Partnering with AVS, the AMRC was able to leverage the design flexibility only possible through AM to create a new fuel tank design. This was achieved by undertaking a detailed body of work that went from prototyping, section IV, to detail design, section V, 3D printing section VIII, and testing, section IX. Each section consisted of many elements that contributed to the development of DfAM methodologies, identifying challenges and project achievements. These are summarised below:

<u>DfAM methodologies</u>

- Being able to verify design changes is key, otherwise concepts remain as a concept – this is in reference to the variable wall thickness attempts using image mapping of stress plots, which could only be generated as an output STL CAD model, and were therefore not suitable for FEA, section VI.
- Process simulation is an asset in the digital workflow and should be used prior to part printing to enable the designer to optimise parts with an additional layer of information, section VII.
- The metal AM process is a geometry driven approach. Therefore, existing AM design and manufacturing guidelines may not be able to cater for a 'one size fits all' approach.

<u>Challenges</u>

- A highly fragmented software workflow was used for design, optimisation, FEA, printability, supports, slicing, and analysis. Challenges are created in tracking design changes and also the need for the designer to be proficient in multiple software packages, see Figure 3.
- Although topology optimisation identified the most efficient fuel tank form, it was time-consuming in finding a balance between the structure, manufacturing constraints, and process simulations.

<u>Project Achievements</u>

- The final fuel tank mass was 360 g which was a 28 % decrease in weight when compared to the original dry mass of 500 g, improved on the desirable target mass of 368 g and is similar to the mass of a spheroidal fuel tank.
- The volume utilisation of the cuboidal fuel tank was estimated at 90 % which is an improvement when compared to spherical tanks at approximately 60 % [2].
- The fuel tank can hold approximately 2.8 times the fuel volume of a 78 mm diameter sphere and 1.47 times the fuel volume of a 96 mm diameter sphere.
- During testing, the fuel tank withstood all non-destructive tests without observable deformation. The fuel tank ruptured at 74 bar, which is 1.9 times the safety factor of the design burst pressure specified in ECSS-E-ST-32-02C REV 1[10].
- The AMRC was able to demonstrate the benefits of metal AM in manufacturing a novel fuel tank design. The fuel tank cannot be manufactured via conventional methods.

Through the MiniTANK project, it was demonstrated that metal AM is an alternative route for the manufacture of complex fuel tank designs. For commercial use, further work is required to determine the cost vs benefit model of using metal AM technology as a viable production route. This is typically driven by the suitability of the geometry for metal AM and also the market need. Fuel tanks, in particular for CubeSat applications, are ideal as they can be categorised as a high-value product that is manufactured at relatively low quantities.

<u>Assessment of TRL achieved</u>

The MiniTANK project started at TRL4 as a result of preliminary studies carried out by Teng and Jin [2] in 2017. These studies developed a metal AM fuel tank with internal supports. However, the work was limited in that it only considered one type of internal lattice structure and external shape optimisation. The design did not consider advanced lattice or structural configurations such as honeycombs, diamond, stochastic or graded lattices, wicking features or hollow walls for weight reduction and thermal insulation.

MiniTANK has successfully brought the concept to TRL6 with the inclusion of a selection of the above mentioned complex features, resulting in a detailed model representative in the form, fit, and function necessary to be integrated on board a CubeSat; and whose performance has been verified in a relevant environment. TRL definitions are given in the ECSS-E-AS-11C [12] documentation. Further assessment and verification of this achievement may be given at the discretion of the UKSA.

## XI.Conclusions and recommendations

The MiniTANK project was able to demonstrate the successful application of AM in order to achieve performance benefits in a component not manufacturable through conventional manufacturing methods. The learnings from this project can be used at a larger system-level scale, which would include the optimisation of multiple part assemblies, in order to achieve greater mass reduction targets. An example of this could be the optimisation of a complete CubeSat or larger satellite system.

Following the MiniTANK test results, data suggests that a future work programme could focus upon lightweighting the fuel tank further, as it was able to withstand an applied pressure of up to 74 bar. Work could also be focused upon improving the as-built microstructure and phase transformations by controlling the in-situ thermal gradients, in order to achieve improved mechanical properties. It is also recommended to explore post-processing techniques such as shot peening and Hot Isostatic Pressing (HIP) in order to improve the fatigue performance of the fuel tank.

To aid in the development of current AM software and minimise fragmentation of workflows, much-improved end to end packages are required. At the time of writing, software vendors such as Autodesk and Dassault Systèmes have already released software that would be of benefit to future work programmes.

## Acknowledgments

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