Australian National University

Mechanical Subsystem Design

Prepared For

Advanced Instrumentation and Technology Centre

ANU College of Engineering and Computer Science

Prepared By

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Acronyms

ANU Australian National University.

BTO Beam Transfer Optics.

CF Carbon Fibre.

EOS Electro-Optic Systems.

FEA Finite Element Analysis.

GSL Guide Star Laser.

ISA Injection-Seeded Amplifier.

LH Laser Head.

OOS Out of Scope.

SFG Sum Frequency Generator.

SHS Square Hollow Section.

1 Introduction

The Mechanical Subsystem Design relates to the physical mounting of the Australian National University (ANU) and Electro-Optic Systems (EOS) Guide Star Laser (GSL) Laser Head (LH)s to the 1.8m telescope and the vibration requirements.

2 Mounting

Mounting relates to the physical mounting of the ANU and EOS GSL LH to the 1.8m telescope. The LHs are to be mounted on the EOS CF breadboards, which shall ideally be mounted on the mounting plate on the observation level.

2.1 Requirements

The requirements for the design of the mounting frame are taken from the system subsystem document [1], and are reproduced here. These requirements are listed in Table 1.

Table 1: Mechanical System Requirements (mounting)

Reference	Description
1.1.2	The telescope dictates that the System not obtrude more than 1000mm from the 1.8m telescope mounting position.
1.1.3	The telescope dictates that the System shall not extend more than 610mm above the 1.8m telescope's mounting plate on the left side.
1.1.4	The telescope dictates that the System shall not extend above the 1.8m telescope's mounting plate on the right side.
1.1.5	The telescope dictates that the System shall not place more than 50MPA on any bolt into the telescope.
1.1.6	The telescope dome dictates that all systems components be able to pass through the entry level door or the observation shutters.
1.1.7	The telescope dome dictates that the observation shutters have dimensions of 1800mm by 2900mm for the purpose of passing components into the dome.
1.1.10	The telescope dictates that the System shall [ideally] be mounted to the telescope using no more than the available holes.
2.1.1	The EOS GSL dictates that the LH be mounted on either 2 or 3 carbon fibre breadboards.
2.1.2	The EOS GSL dictates that the System includes breadboards with dimensions of 1500 × 750 × 105 mm (l×w×h).
2.1.3	The EOS GSL dictates that the minimum spacing of 250 mm exists between breadboards.
2.1.4	The EOS GSL dictates that the gravitational orientation of the System does not change after the EOS GSL is mounted and calibrated.
2.1.5	The EOS GSL dictates that the 3 EOS GSL breadboards be aligned such that all through holes are concentric.
2.1.6	The EOS GSL dictates that the space between concentric through holes of the EOS GSL breadboards are not obstructed.
2.1.7	The EOS GSL dictates that the System include 3 EOS GSL breadboards each with optical components weighing 150 ± 50kg.
3.1.1	The ANU GSL dictates that the ANU shall account for a LH of 610 × 305 ×305 mm (l×w×h).
3.1.2	The ANU GSL dictates that the LH be mounted the EOS carbon fibre breadboard on which the Beam Transfer Optics (BTO) are mounted.

2.2 Concepts

At this stage of the project, either 2 or 3 of the EOS CF breadboards would be required to mount the LHs for the ANU and EOS GSLs. The exact number was uncertain due to frequent changes to the EOS GSL LH packaging and uncertainty of the ANU GSL LH size.

Concepts for mounting 2 and 3 breadboards on the 1.8m telescope were developed and are provided in Figures 1 and 2. The principles for each concept are:

1. A single structure used to mount all breadboards to the 1.8m telescope
2. The structure is mounted to the 1.8m telescope mounting plate
3. The ANU GSL LH mounted on the breadboard on which the BTO are mounted
4. BTO aligns with the central elevation axis port of the 1.8m telescope

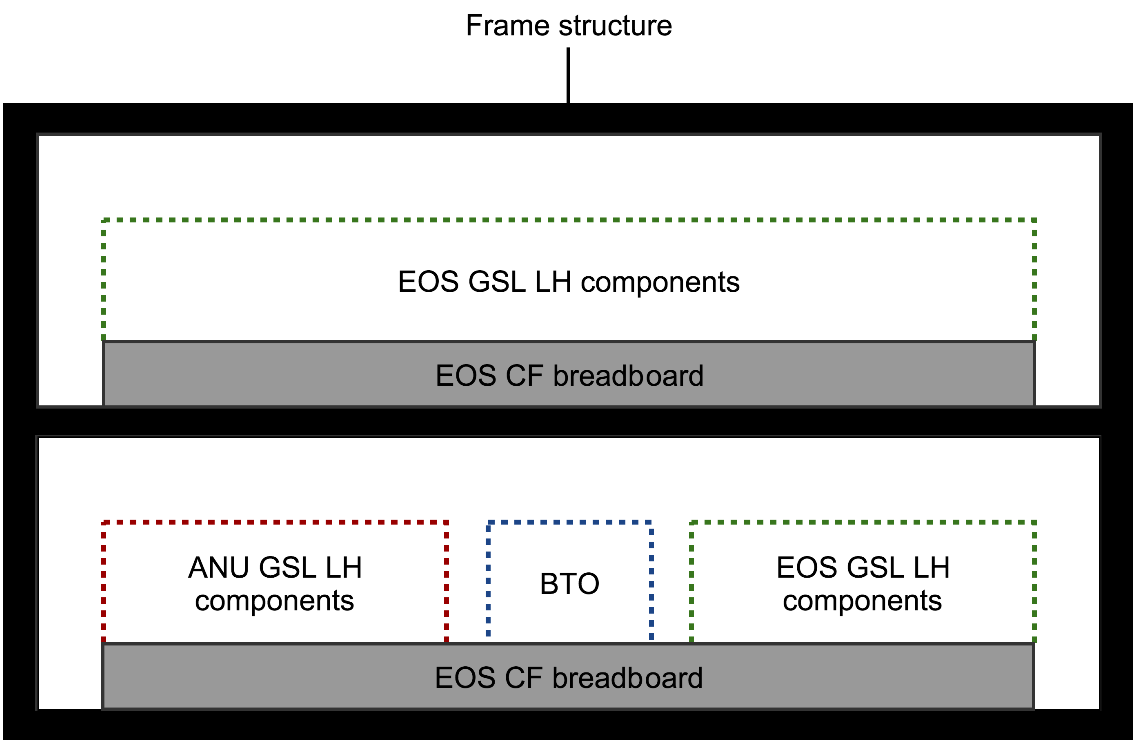


Figure 1: Concept for a 2-tiered mounting frame

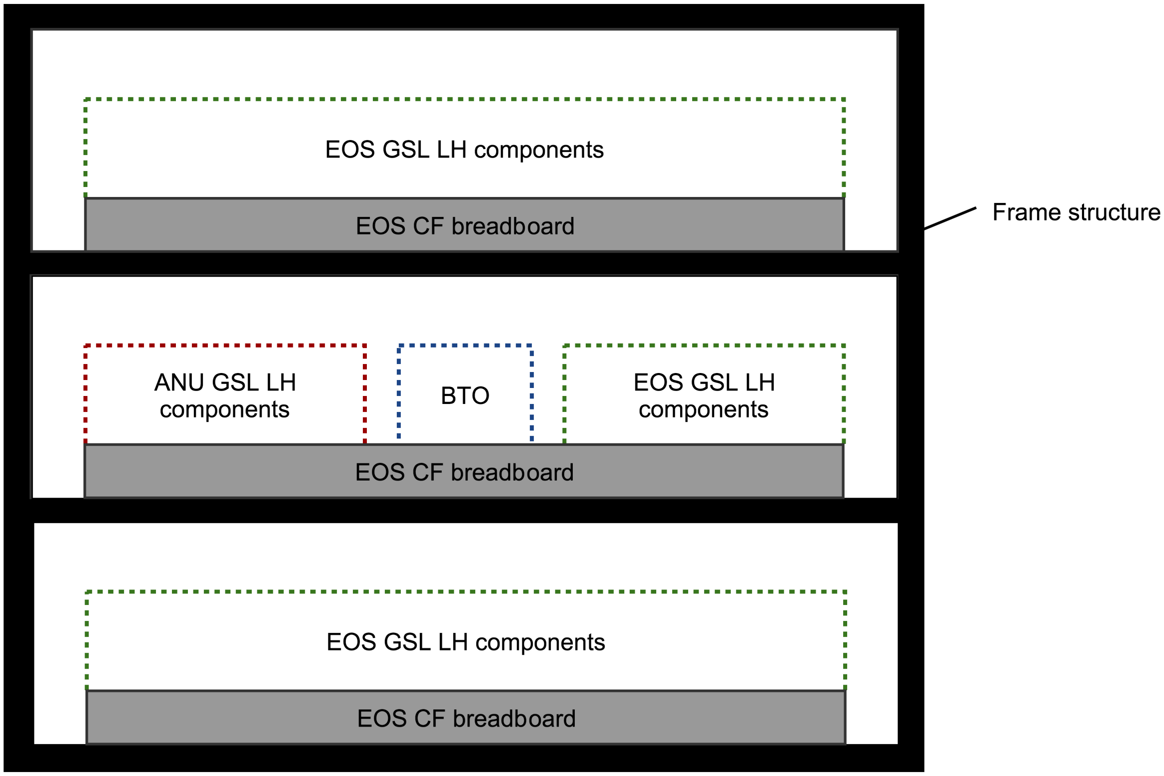


Figure 2: Concept for a 3-tiered mounting frame

2.3 Design

At this stage of the project, the use of 2 CF breadboards is the most likely scenario [2]. A detailed design for a 2-tiered mounting frame was developed for this scenario and is presented in this report. A detailed design for the alternative scenario, a 3-tiered mounting frame for 3 CF breadboards, was considered Out of Scope (OOS) due to time constraints.

2.3.1 Overview

The 2-tiered mounting frame model is presented in Figure 3.

The members of the mounting frame are constructed from Square Hollow Section (SHS) CF tubing. The members are connected using CF gusset plates and CF inserts.

The mounting frame has three horizontal levels of CF tubing, with the lower and middle levels directly supporting the breadboards. The upper level was included to provide attachment points for insulating panels, but is not loaded by the breadboards.

The breadboards are supported by horizontal CF tubing set inside the frame. This allows the breadboards to be directly inserted through the front of the frame. The frame is also sufficiently wide to ensure the

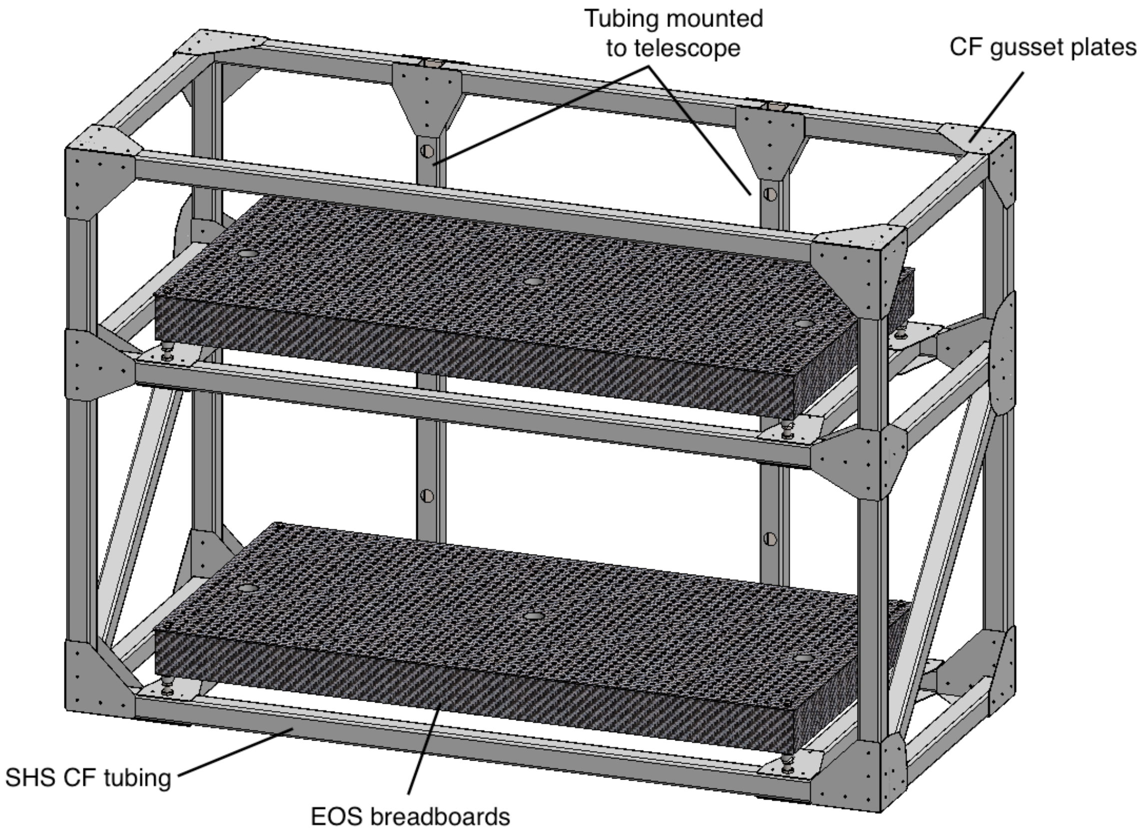


Figure 3: Model of the 2-tiered mounting frame

breadboard insertion is not obstructed by gusset plates.

The vertical CF tubing at the frame corners supports and transfers loads from the horizontal tubing. Additional vertical CF tubing at the rear of the frame aligns with the M8 holes in the telescope mounting plate. These are the only members fixed to the telescope.

Diagonal CF tubing is used on the sides of the frame to reduce deformation resulting from vertical loading. Loading in other directions is insignificant and additional diagonal bracing was considered unnecessary.

2.3.2 Material Selection

CF composites were considered for the frame material at the recommendation of EOS [3]. An advantage of CF composites is high strength to weight ratio compared to alternatives such as steel and aluminium. The reduction in weight reduces loading on the telescope and will present fewer logistic issues for transport to the telescope. CF composites also have low coefficient of thermal expansions. This reduces the risk of laser misalignment resulting from temperature variations.

DragonPlate CF/epoxy composite components were considered for the design. This was due to the availability of pre-fabricated hollow section tubing suitable for lightweight framing in high strength applications.

2”x2” SHS tubing was selected for the design. DragonPlate also supplies pre-fabricated CF gusset plates for tubing interconnections. 2” square tube CF gusset plates were used due to their compatibility with the selected SHS tubing size. The design also includes components manufactured from DragonPlate quasi-isotropic CF/epoxy composite angle and sheets at tubing interconnections. Available specifications for the DragonPlate components are provided in the Appendix.

2.3.3 Tubing interconnections

A tube interconnection is presented in Figure 4.

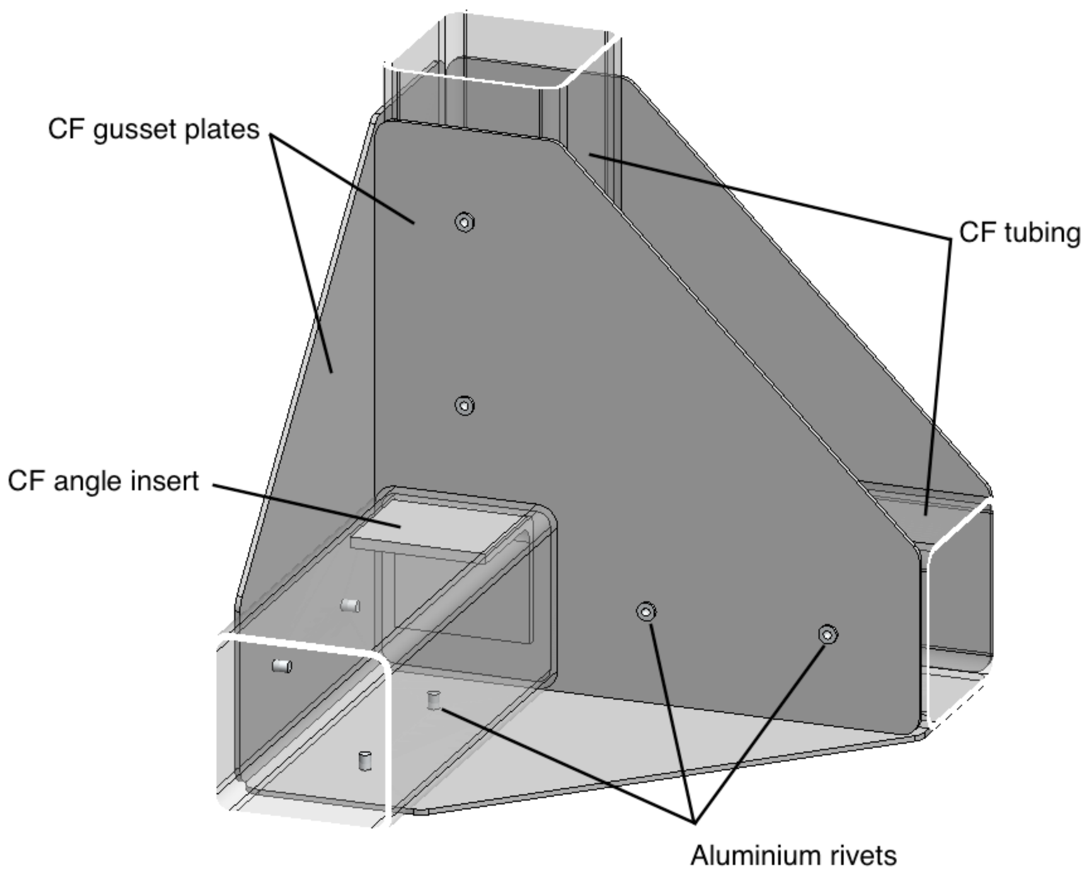


Figure 4: SolidWorks model of a tube interconnection

The CF tubing is connected using the method recommended by DragonPlate [4]. Gusset plates are used at the connections and bonded to the tubing using Scotch-Weld adhesive. 0.125” aluminium rivets are used at locations defined by the pre-fabricated holes in the gusset plates. The rivets are used to hold gusset plates in position while the adhesive cures.

Pre-fabricated gusset plates are used where possible to minimise the construction time and difficulty. The frame geometry did not allow pre-fabricated gusset plates to be used for interconnections of the horizontal tubing that directly supports the breadboard. Custom sized gusset plates manufactured from quasi-isotropic CF sheets were used at these locations.

Where possible, two gusset plates were used to connect two tubing members to minimise torsional deformation resulting from asymmetric load transfer. This was not necessary for the upper layer of horizontal tubing due to small applied loads. The double-gusset connection was not possible for horizontal tubing on the side of the frame due to gusset arrangement. CF angle inserts are used to compensate for this.

2.3.4 Breadboard interface

The breadboards are mounted to the frame using ball adjusters and steel inserts. This assembly is presented in Figure 5.

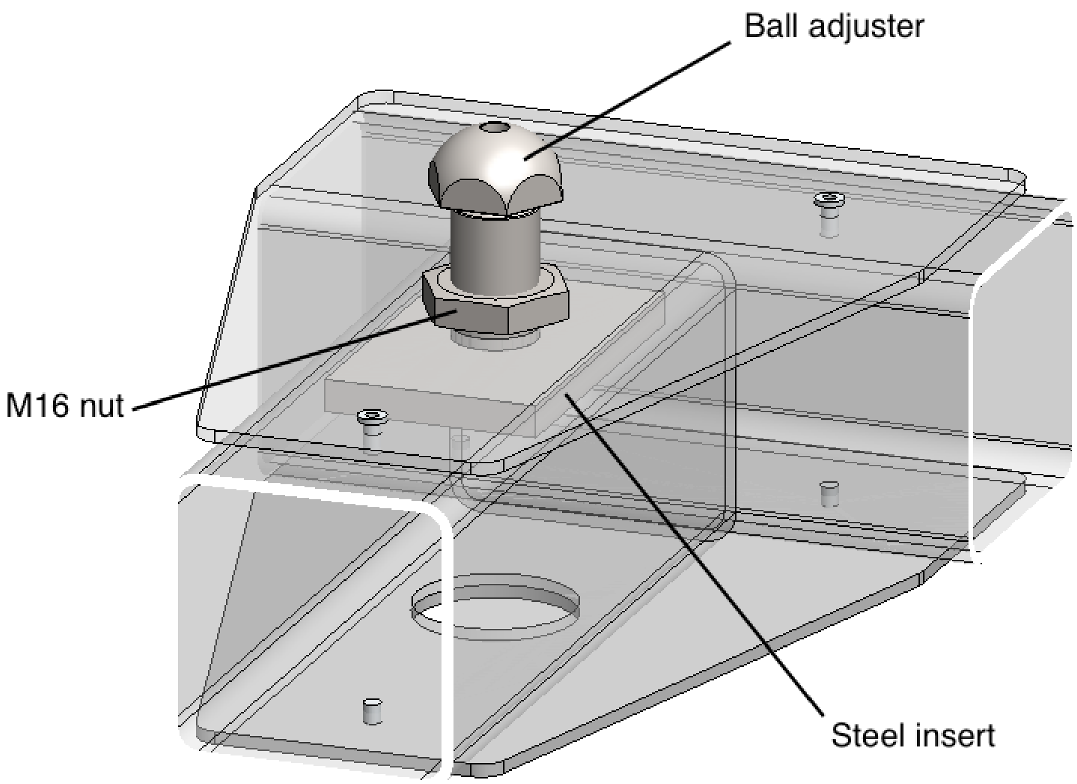


Figure 5: SolidWorks model of the breadboard interface

The ball adjuster is frequently used by EOS [5] and ensures concentric alignment of breadboard through-holes. This component is fixed to the frame using two M16 nuts that permits small height adjustments to achieve BTO alignment with the central elevation axis port. Steel inserts are also used to distribute the load applied to the CF tubing and reduce the risk of crushing. Concentric 30mm holes on the the underside of the CF tubing allow insertion and adjustment of the lower M16 nuts.

2.3.5 Mounting plate interface

The frame is mounted to the telescope using steel inserts and M8 bolts. This assembly presented in Figure 6.

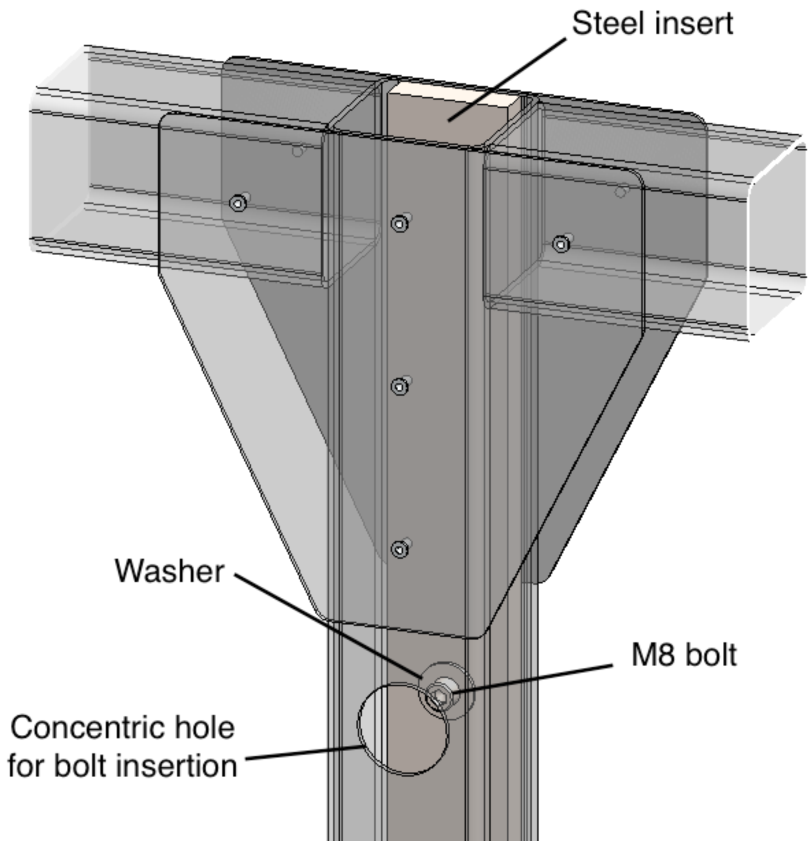


Figure 6: SolidWorks model of the mounting interface

Steel inserts are used to distribute the load applied to the CF tubing and reduce the risk of crushing. The assembly utilises the existing M8 holes in the mounting plate. Hole positioning was selected to ensure alignment of the BTO with the central elevation axis port. Concentric 30mm holes in the vertical CF tubing allow insertion of M8 bolts to mount the frame to the telescope.

2.4 FEA Modelling

Finite Element Analysis (FEA) modelling was undertaken to assess the viability of the proposed frame design. Time constraints in the project only allowed for simplified modelling using one-dimensional elements. The frame was modelled as a series of rigidly connected CF tubes with constant cross-section. Other components, features and holes in the tubing were not incorporated into the model. Material assumptions were also required. As a result, the simulation results are only used to indicate the suitability of the DragonPlate tubing.

2.4.1 Material approximation

The DragonPlate CF/epoxy composite was modelled as an isotropic material due to time constraints. This was considered appropriate for an initial analysis given the composite approximates a quasi-isotropic laminate, which exhibit behaviour similar to isotropic materials [6]. The effective engineering constants used in the FEA model were determined using material properties of a similar CF/epoxy composite. This was necessary given complete mechanical properties of the DragonPlate composite were unavailable. The calculation of the effective engineering constants is provided in the Appendix.

2.4.2 ANSYS model

The mounting frame was modelled as a space frame using one-dimensional elements in ANSYS R16.1. Each line element corresponds to the central axis of a CF tube. The line elements were assigned the SHS cross section of the DragonPlate tubing used in the frame.

The model and boundary conditions are presented in Figure 7.

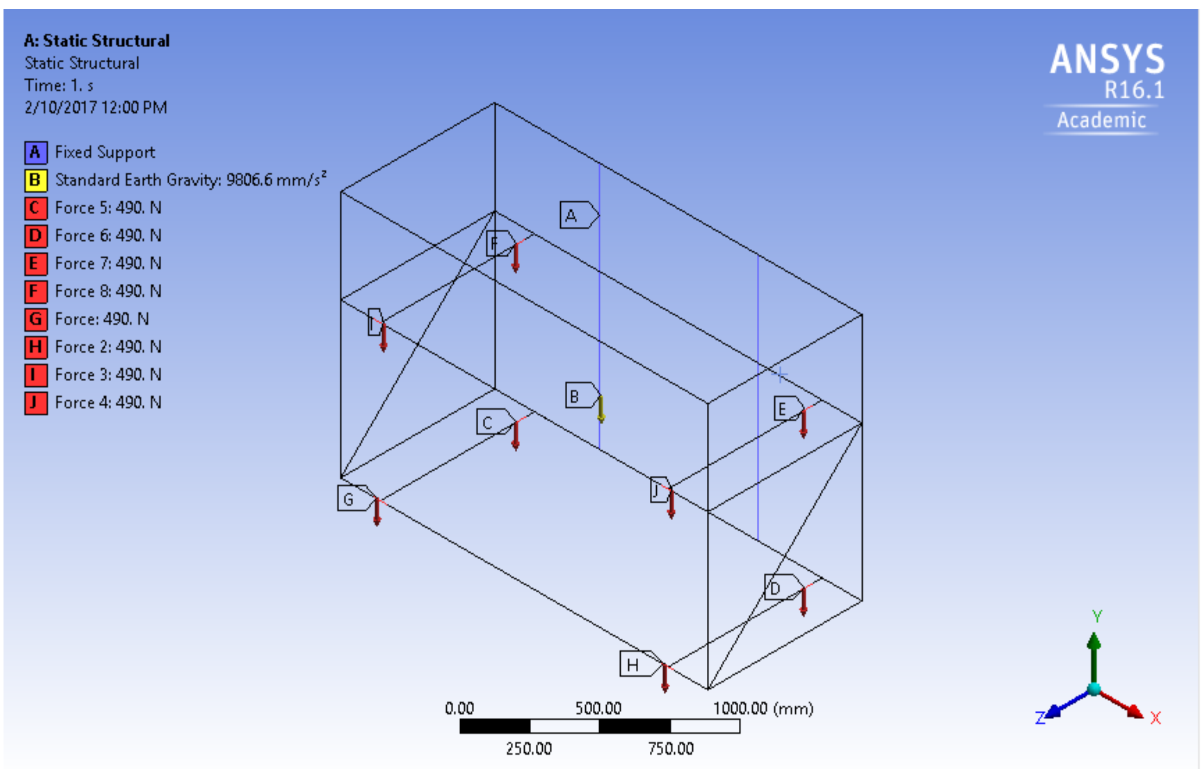


Figure 7: ANSYS model and boundary conditions

The vertical CF tubes fixed to the telescope mounting plate were modelled as fixed supports. The total mass of the each breadboard and LH components could not be confirmed at this stage in the project. This mass was assumed to be 200 kg in the analysis (the upper limit in Requirement 2.1.7). Even mass distribution across the breadboard was assumed and thus, the load applied by each breadboard was distributed evenly across the four points of contact. Standard gravitational loading was also applied.

An initial mesh was generated in ANSYS using default settings and the model was solved for the stated boundary conditions. Critical stress locations were identified and the mesh in these areas was refined by reducing the local element size. The model was considered to converge when the variation in maximum stress between two incrementally refined meshes was less than 1%.

2.4.3 Results

Simulation results for total deflection, maximum combined stress and minimum combined stress are presented below. Maximum combined stress is the stress resulting from axial and maximum compressive bending stress in the tube cross section at a given location. Similarly, minimum combined stress is the stress resulting from axial and maximum tensile bending stress.

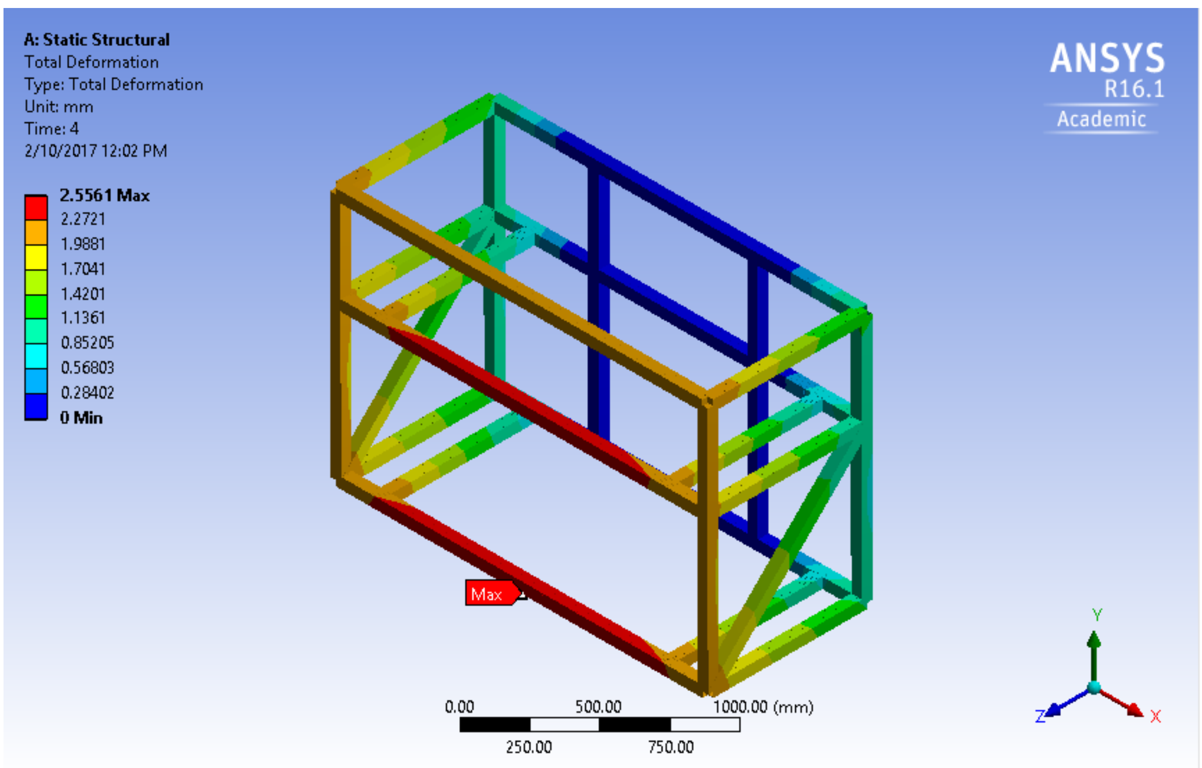


Figure 8: Total deformation of mounting frame under loading (mm)

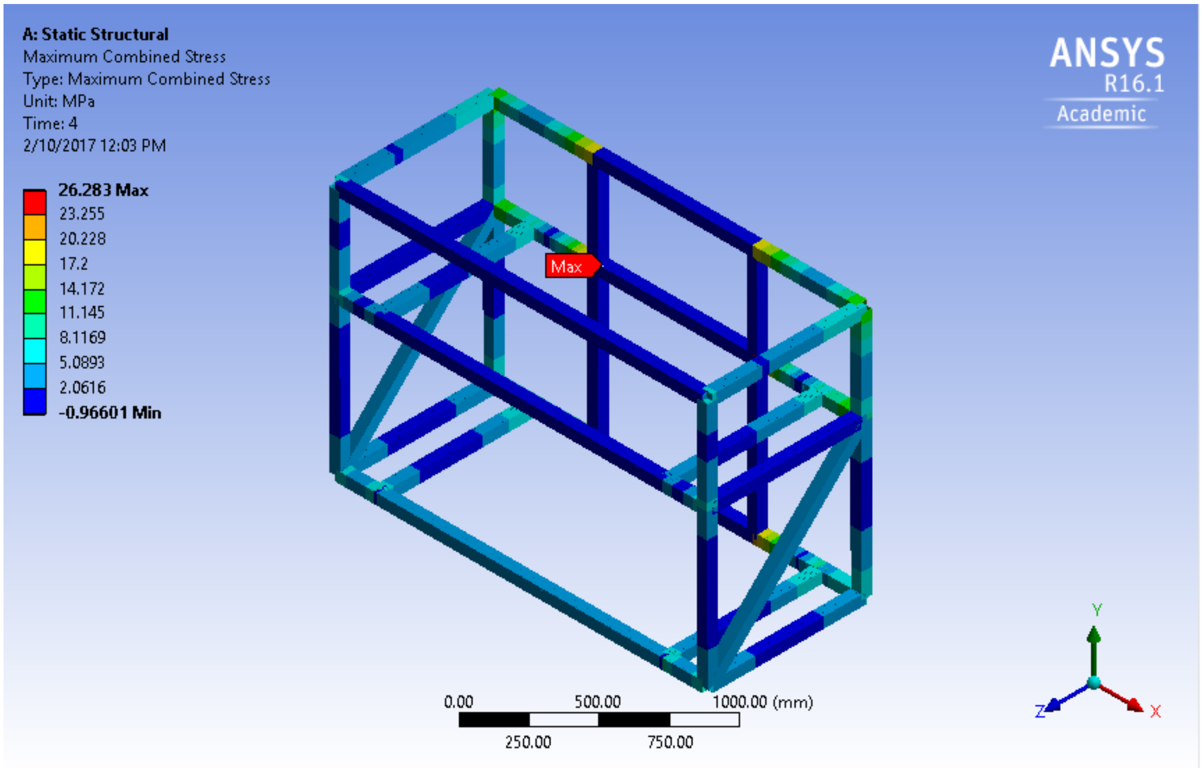


Figure 9: Maximum combined stress of mounting frame under loading (MPa)

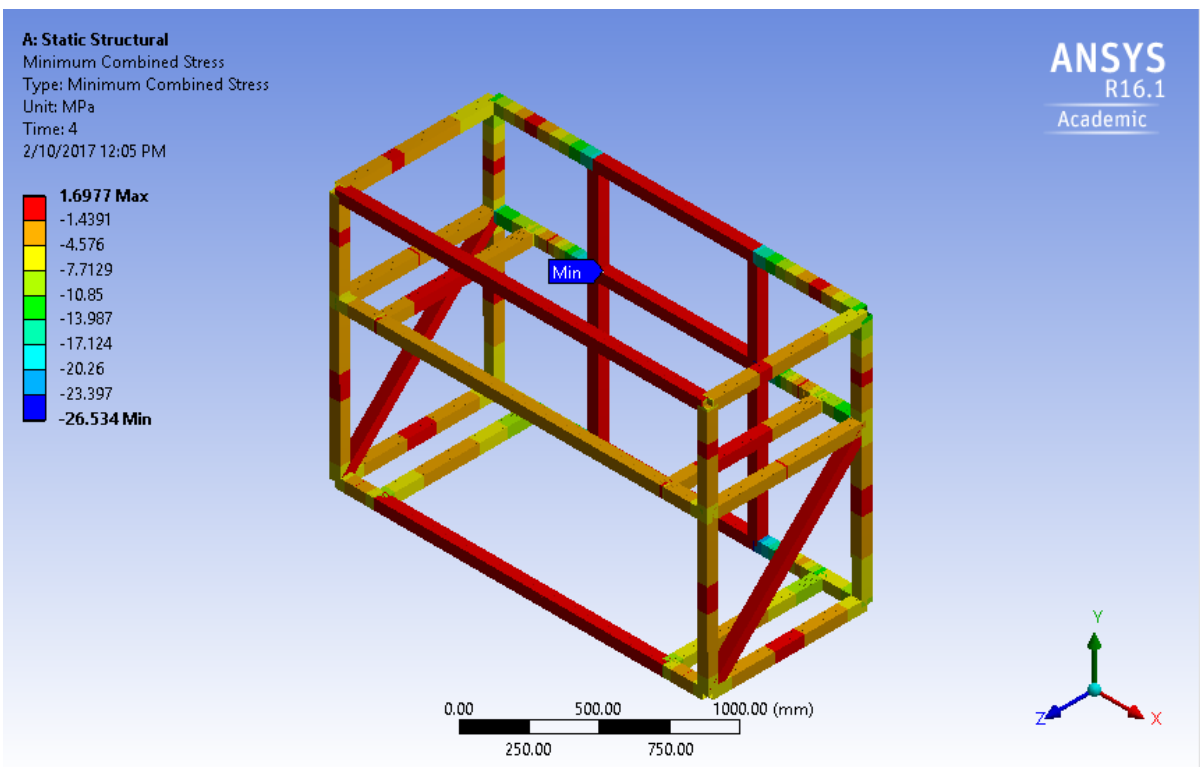


Figure 10: Minimum combined stress of mounting frame under loading (MPa)

As discussed previously, the accuracy of the simulation is limited by the simplified model and required assumptions. The results are considered as a rough approximation to determine if the DragonPlate tubing is a suitable candidate material.

Figure 8 indicates the deflection at the breadboard/tubing contacts is less than 2.56mm. The ball adjusters can compensate for deflection on this scale to achieve alignment of the BTO with the central elevation axis port.

The strengths of a CF/epoxy composite with similar weight fraction was considered due to the unavailability of the DragonPlate composite strengths. The lamina directional strengths are as follows [7]:

$$
\begin{aligned}
S_L^{(+)} &= 1500\text{MPa} \\
S_L^{(-)} &= 1200\text{MPa} \\
S_T^{(+)} &= 50\text{MPa} \\
S_T^{(-)} &= 250\text{MPa}
\end{aligned}
$$

The minimum strength is transverse tensile strength ($S_T^{(+)}$) at 50MPa. This is the expected direction of failure given the lay-up schedule and considering it is significantly lower than the other directional strengths. Although stress interaction effects are complex, an orthogonal tensile stress greater than 50MPa in the CF tubing would be required to achieve failure given the lay-up schedule. The maximum tensile stress from ANSYS simulation was 26MPa, indicating that the tubing will not fail under the applied loads.

The ANSYS modelling indicates the DragonPlate CF tubing is suitable for the mounting frame in regards to stiffness and strength.

2.5 Recommendations

It is recommended that the further verification of the proposed design is undertaken. This includes:

- Detailed FEA analysis of the full model, incorporating all features and modelling of CF components as anisotropic
- Mechanical testing of DragonPlate tubing, angle and sheets to determine material properties (stiffness, strength, coefficient of thermal expansion and density)
- Mechanical testing of interface strength between DragonPlate components joined using Scotch Weld Adhesive
- Accurate modelling of load and load distribution due to breadboards and LH configuration as this information becomes available
- Incorporation of other subsystem components into the model and analysis as this information becomes available.

3 Vibration

Both lasers have vibration-sensitive components, and various mounting options have been considered. Major design concerns are laser output power deterioration due to vibration and the BTO mirror compensating for vibration. The first problem is mitigated by adding vibration dampening, while the mirror in BTO could be outfitted with an active beam centring device.

The previous team relied on vibration testing done by Stuchbery [12], however the EOS laser components have been updated since then and their vibration tolerance has changed [8].

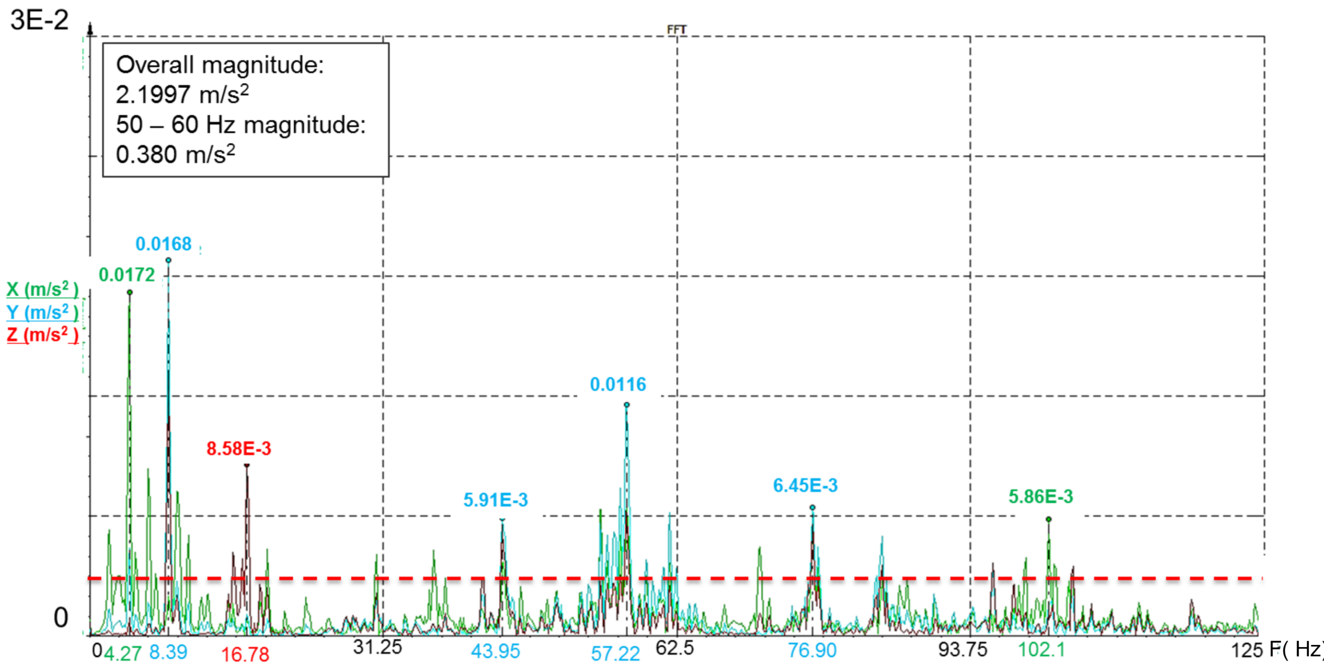


Figure 11: Spectrum of the vibrations present at the telescope when all systems are at rest [12]

3.1 Requirements

The vibration requirements are taken from the system subsystem document [1], and are reproduced here. These are summarised in Table 2.

Table 2: Vibration System Requirements

Reference	Description
1.5.4	The telescope dictates that the System shall account for a maximum vibrational input of as specified by the power spectral density specified in figure 11
2.1.14	The EOS GSL requires that the System accounts for the currently unknown vibration from the coolers.
2.5.4	The EOS GSL requires that it is not exposed to vibration an order of magnitude greater than (?) (vibration tolerances are unknown)

3.2 Design

The EOS laser head contains vibration-sensitive components and will most likely require dampening [9]. The vibration-sensitive components of the EOS laser, in order of decreasing sensitivity [8], are as follows:

1. Oscillators
2. Injection-Seeded Amplifier (ISA) - will have similar sensitivity to the Sum Frequency Generator (SFG))
3. SFG.

The oscillators will be mounted in the clean room, where vibration is less significant. Communication and optical signals from the oscillators will be routed to the telescope using Fibre-optic and Ethernet cables.

The ISA is not currently mounted, however it will likely be mounted on a breadboard. The SFG will be mounted on output breadboard. These components will be subject to vibration present in the dome (Figure 11). Beam centring mirror needs to compensate for vibration of the output beam.

3.3 Testing

The vibration of the mounting plate was tested while the dome was moving. A 10 mV/g, 3-axis accelerometer was installed on the side of the telescope mount. The x, y and z axis of the accelerometer corresponded to vertical, transverse and surface-normal vibrations respectively. The telescope was rotated and elevated at maximum speed to simulate the worst-case vibration scenario that would occur during GSL operation. Data was recorded at 20 kHz.

The results of the vibration test are presented in Figure 12. Transverse vibration peaked at 0.02 ms^{-2} at approximately 100 Hz. Vertical and surface-normal vibration both peaked at 0.015 ms^{-2} at approximately 50 Hz. The 50 Hz peak is present on all axis and was most likely caused by coolers or other electrical devices, given it is at the power supply frequency.

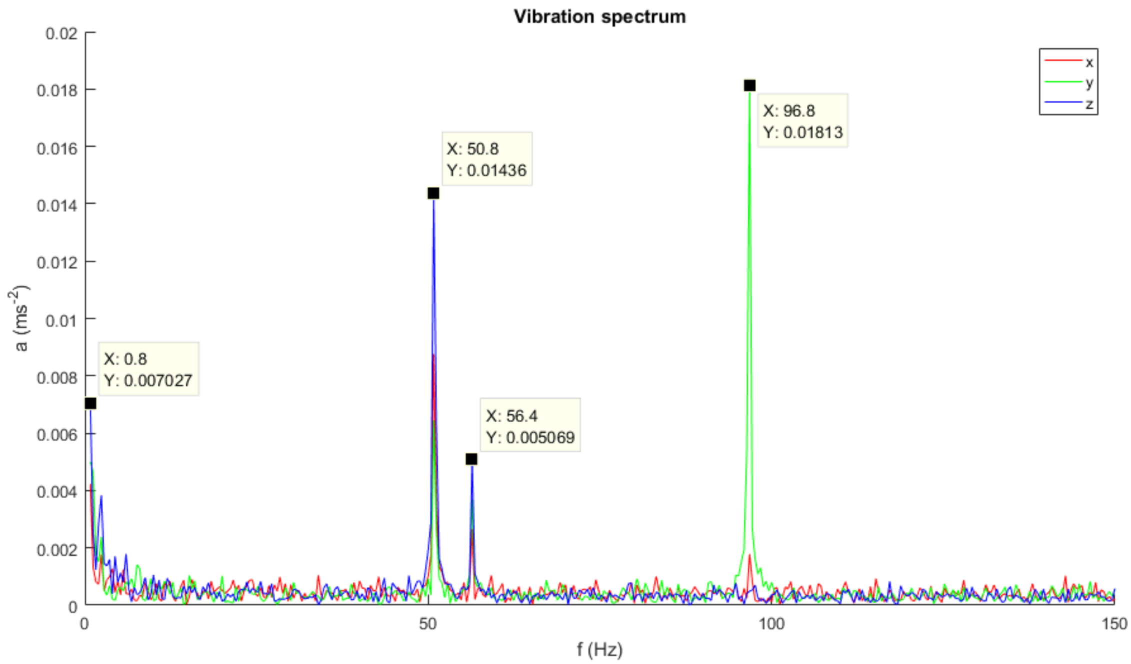


Figure 12: Spectrum of the vibrations present at the telescope when the dome is moving

3.4 Recommendations

To determine the extent to which the vibration-sensitive components need to be dampened, further testing is required. This includes:

- Testing the vibrational sensitivity of the EOS laser in the current configuration
- Determining the vibrational spectrum of the clean room, where the oscillators will be mounted

The methodology for such experiments is presented in [12] and can be found in Appendix C.

References

[1] "Updated system subsystem requirements," October 2017.

[2] J. Webb, "Personal Communication 18/08/17."

[3] M. Blundell, "Personal Communication 18/08/17."

[4] DragonPlate. Gusset assembly instructions. Manual. Accessed 5 October 2017. [Online]. Available: https://dragonplate.com/docs/GussetAssembly.pdf

[5] M. Blundell, "Personal Communication 15/09/17."

[6] R. F. Gibson, *Principles of Composite Material Mechanics (Third Edition)*. Boca Raton, Florida: CRC Press, 2012.

[7] Performance Composites. Mechanical properties of carbon fibre composite materials, fibre / epoxy resin (120°c cure). Accessed 1 October 2017. [Online]. Available: http://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp

[8] J. Webb, "Personal Communication 08/09/17."

[9] G. Fetzer, "Personal Communication 22/09/17."

[10] DragonPlate. Carbon fibre rectangular tube: Material specifications. Accessed 6 October 2017. [Online]. Available: https://dragonplate.com/docs/DPSpecRecTube.pdf

[11] ——. Carbon fibre angle: Material specifications. Accessed 6 October 2017. [Online]. Available: https://dragonplate.com/docs/DPSpecAngle.pdf

[12] A. Stuchbery and E. Thorn, "Vibrational and Thermal Measurements of Laser Guide Star Adaptive Optics for Tracking Space Debris." AITC, Canberra, Australia, Jan. 2015.

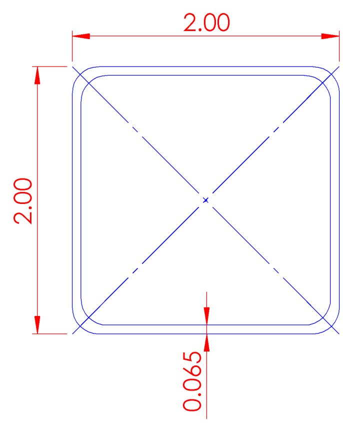
Appendix

A DragonPlate specifications

A.1 CF rectangular tube

Available at [10]

Cross-section schematic (all dimensions in inches):



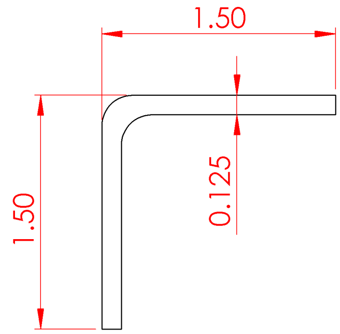
Material specifications:

Property	Description
Lay-up schedule	$[\pm 45°/\bar{0}]_s$: $\pm 45°$ bi-axial CF braid, 0° uni-directional CF, $\pm 45°$ bi-axial CF braid
Resin	Epoxy resin, W_f = 0.5
Braid fibre properties	Tensile strength = 640 ksi, Modulus of elasticity = 34 Msi
UNI fibre properties	Tensile strength = 640 ksi, Modulus of elasticity = 34 Msi

A.2 Quasi-isotropic CF angle

Available at [11]

Cross-section schematic (all dimensions in inches):



Material specifications:

Property	Description
Lay-up schedule	[0/90, ±45, 0/90, ±45, 0/90, ±45, 0/90, ±45, 0/90, ±45, 0/90, ±45, 0/90]: all layers unidirectional CF
Resin	Epoxy resin, W_f = 0.5
UNI fibre properties	Tensile strength = 512 ksi, Modulus of elasticity = 33.4 Msi

B Isotropic approximation DragonPlate CF/epoxy composite for ANSYS modelling

The effective extensional engineering constants for quasi-isotropic laminates can be approximated by the following [6]:

$$\tilde{E} = \frac{(U_1 - U_4)(U_1 + U_4)}{U_1}$$

$$\tilde{G} = \frac{U_1 - U_4}{2}$$

$$\tilde{v} = \frac{U_4}{U_1}$$

where U_1 and U_4 are invariants given by the following:

$$U_1 = \frac{3Q_{11} + 3Q_{22} + 2Q_{12} + 4Q_{66}}{8}$$

$$U_4 = \frac{Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66}}{8}$$

and 'Q' terms are related to the longitudinal modulus (E_1), transverse modulus (E_2), shear modulus (G_{12}), and major Poisson's ratio (v_{12}) of a unidirectional lamina. These relationships are given by the following equations:

$$Q_{11} = \frac{E_1}{1 - v_{12}v_{21}}$$

$$Q_{12} = \frac{v_{12}E_2}{1 - v_{12}v_{21}}$$

$$Q_{22} = \frac{E_2}{1 - v_{12}v_{21}}$$

$$Q_{66} = G_{12}$$

$$v_{21} = \frac{E_2 v_{12}}{E_1}$$

The lamina mechanical properties for the DragonPlate CF tubing was unavailable. As a result, the following mechanical properties of a unidirectional lamina with similar fibre weight fraction were used [7]:

$$E_1 = 135GPa$$

$$E_2 = 10GPa$$

$$G_{12} = 5GPa$$

$$v_{12} = 0.30$$

The corresponding effective extensional engineering constants were determined:

$$\tilde{E} = 52.40GPa$$

$$\tilde{G} = 19.99 GPa$$

$$\tilde{v} = 0.3106$$

C Vibration testing

Adapted from [12].

C.1 Equipment

1. PCB J356B18 1000 mV/g accelerometer
2. Sirius ACC
3. Type 4294 Bruel & Kjaer calibration exciter
4. Appropriate accelerometer cabling
5. Adhesive mounting wax

C.2 Methodology

1. Mount accelerometer on the optical bench
2. Connect accelerometer to ACC
3. Connect laser's photo diode to ACC
4. Introduce various vibrations to the system and log data