Optical Bench Assembly for the Near Infrared Camera

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ABSTRACT

The Near Infrared Camera is the primary imaging instrument on the James Webb Space Telescope. This instrument operates in the wavelength range of 0.6 to 5 microns and at a temperature of 35K. Two mirror-image optical paths or modules are utilized to provide two adjacent fields of view for science observations and redundancy for the purpose of wavefront sensing. All optical components are supported and aligned by an Optical Bench Assembly consisting of two benches mounted back to back. Each optical bench is a closed back Beryllium structure optimized for mass and stiffness. The closed back structure is achieved by bonding two machined parts together at the midplane of the structure. Each bench half is an open back structure consisting of a facesheet with machined ribs optimized to provide stiffness and to support along primary load paths. The two benches are integrated with optical components separately and are subsequently joined by bolts and pins to form the Optical Bench Assembly. The assembly is then mounted to interface struts, which are used to mount the instrument within the Integrated Science Instrument Module for integration into the JWST observatory. The design of the Optical Bench Assembly is describing including trade studies and analysis results.

Key words: Beryllium, Optical Bench, NIRCam, James Webb Space Telescope, bonded structure

1. INTRODUCTION

The Optical Bench Assembly (OBA) is the primary structure for the Near Infrared Camera (NIRCam) on the James Webb Space Telescope (JWST). This structure supports two optical paths, called Modules A and B, which comprise the cryogenic portion of the NIRCam Instrument. Electronics used to power and control mechanisms and detectors within the instrument are housed in a separate structure maintained at 293K, which is not discussed here. Modules A and B are mirror images of each other and are required to be separable for purposes of integration and testing. The structure must support and align all optical components and mechanisms as well as supporting baffles, wiring harnesses, alignment devices, thermal sensors and heaters. Primary design drivers include requirements for support of launch loads, cryogenic operating temperature (35K), low mass, high stiffness, excellent dimensional stability, predictable dimensional behavior and high thermal conductivity at 35K. Initial trade studies were performed to choose the appropriate material for this structure. Beryllium I220H was chosen based primarily on mass and stiffness constraints. A design of the bench structure was developed that would meet the driving system requirements and optimize the properties of Beryllium within the manufacturing constraints of the material. This paper will describe the OBA design with descriptions of trade studies and analyses performed.

2. DESIGN DESCRIPTION

2.1 Beryllium Material Choice

The James Webb Space Telescope has very stringent mass requirements, which led to a mass driven decision to use Beryllium for the NIRCam Structure. Beryllium is the most mass efficient structural material known. Other materials considered included graphite/cyanate composite, Silicon Carbide, AlBeMet and Aluminum. The early choice of material was essential in order to develop a design that could be manufactured. The material trade study for the NIRCam Optical Bench Assembly is described in detail in a companion paper [1].

2.2 Back to Back Benches

The NIRCam instrument design, encompassing two mirror-image optical trains, led to a back-to-back design for the optical configuration. The most mass efficient structure to support this configuration would be a single optical bench supporting components on both sides. This design was seriously considered but was ultimately eliminated after consideration was given to the complexities of integration and test. Integration of the components on a vertical bench was considered to be a high risk. In addition, the ability to integrate and test each module separately was desired. These additional requirements led the choice of two separate benches that mount back to back. The benches will be bolted and pinned together to achieve repeatable positioning and to provide additional stiffness. The back-to-back design with the optical components mounted to the benches is shown in Figure 1.

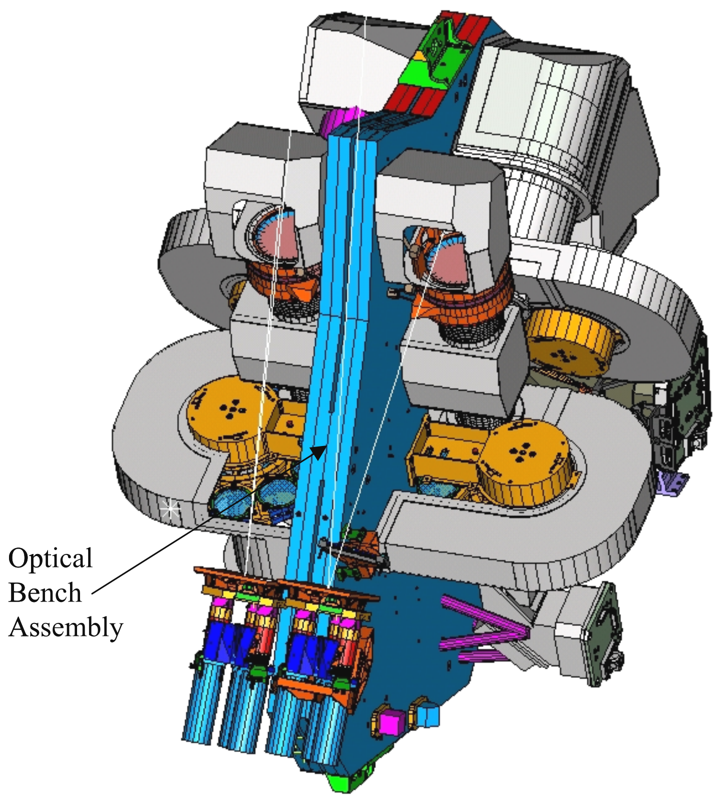

Figure 1: NIRCam Instrument with back to back optical modules supported by two optical benches

2.3 Closed Back Design

The design of each bench was also optimized for mass. The simplest bench design from a manufacturing standpoint would be an open back structure with one facesheet supported by ribs. However, the mass of a closed back structure is substantially less than the simpler open back design. The closed back design has two facesheets separated by a rib structure. For a given fundamental frequency, this design minimizes mass, allows for a thinner overall profile thickness, requires less time to machine pockets and uses less Beryllium material. The challenge to this design is developing a suitable method of manufacturing.

2.4 Manufacturing Configuration

Several configurations were considered for building closed back optical benches. A trade study was conducted to choose the best option. The following methods were considered: two facesheets joined to a separate rib pattern, an open backed structure with a back facesheet attached and two machined open back structures joined along the plane of symmetry. The first two options incorporate separate flat facesheets joined to a rib pattern. This option would best utilize a rolled sheet of Beryllium. Rolled sheet is inherently anisotropic and therefore was eliminated as an option as it would cause dimensional distortion. The third option was chosen because it is symmetric and involves only one joining operation. This configuration was believed to be the most dimensionally stable. Figure 2 illustrates the OBA construction.

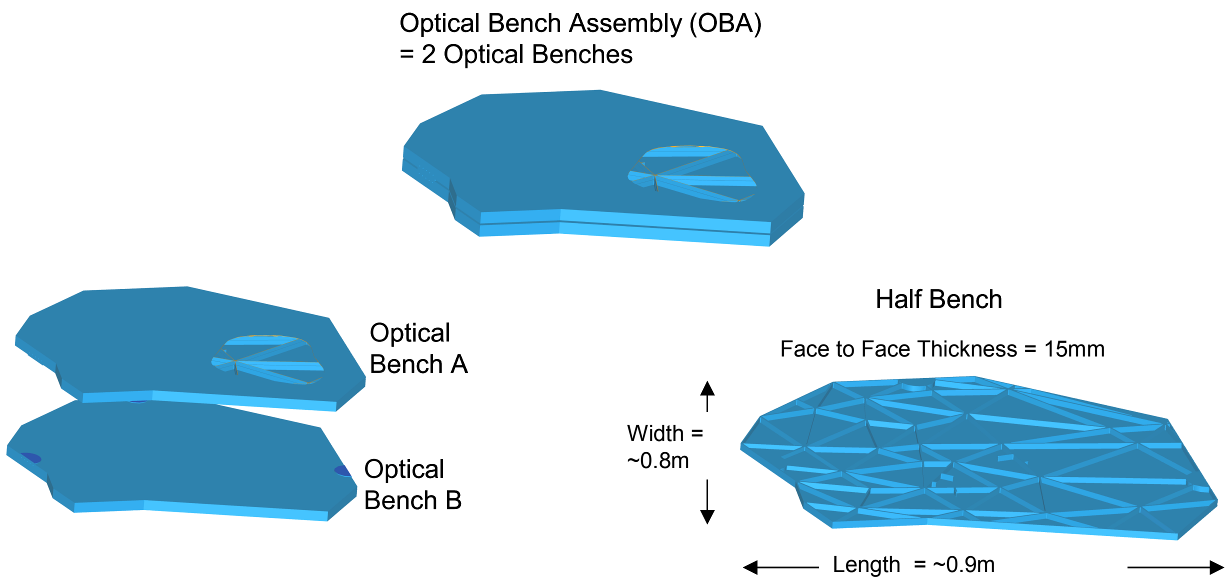

Figure 2:   Optical Bench Assembly configuration showing a portion of the facesheet removed to show the internal rib structure.

2.5 Method of Joining

The next design decision after the configuration was chosen was the method of joining the two half benches together. Choices for joining are bonding, brazing or bolting.

Brazing of Beryllium is a common practice and provides the highest strength of all of the options considered. There are, however, two primary drawbacks to brazing. First, brazing is done at an elevated temperature and the dimensional stability of the optical bench upon cooling to 35K may not be maintained. Second, atmospheric brazing requires flux, which would be nearly impossible to clean adequately on the interior of a closed structure. Vacuum brazing is a relatively new process that holds promise for fluxless joining but still has not fully been developed for large flight structures.

Bolting was considered to be the lowest risk option and could be implemented so that fundamental frequency requirements could be met. This option however has the highest mass and lowest stiffness of the three joining methods considered and was therefore eliminated.

Structural bonding for cryogenic applications has been proven at Lockheed Martin on other flight programs like Gravity Probe B. The methods and adhesives used previously could easily be incorporated on the NIRCam OBA. This method provides good stiffness and adequate strength, can be cleaned to instrument requirements, will provide known dimensional stability and is a lower mass alternative to bolting. Based on these advantages, bonding was chosen as the method to join the two half benches to build each bench module.

2.6 Bench Half Alignment Features

The bottom and top half benches are assembled together after the ribs are machined and are match drilled. Close tolerance pins are used to provide repeatable alignment for the bonding operation. Two pins are used and fit into two holes in one half bench and a hole and a slot in the other half bench. This configuration allows for repeatable assembly and disassembly without over constraining the parts. The two half benches are then held together with 5 bolts. These bolts are used during the dry fit operation and serve to provide protection from bond peel after final assembly.

2.7 Module to Module Attachment

Module A is aligned to Module B in a similar method to the way the half benches are aligned. One module has two close fit holes which locate precision pins. The second module has one hole and one slot which locate on the pins. The pins allow for precision alignment of the modules and carry shear load between the modules. Nine bolts are used to attach the modules together. There is no bonding between the modules so the bolts and pins carry all loads.

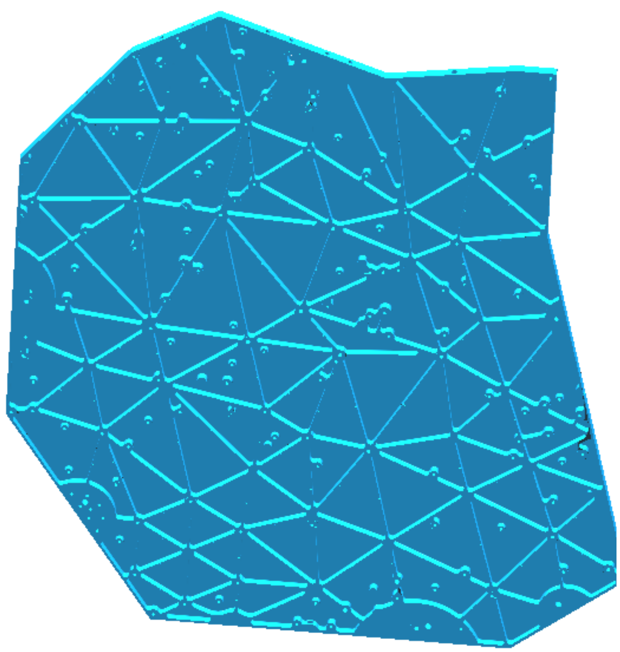

Figure 3: Optical bench internal rib geometry

2.8 Internal Rib Geometry

The internal rib structure within each bench is designed to optimize mass and stiffness. The rib pattern is not an isogrid in that the pockets are not identical. Ribs are placed along primary load paths between the most massive components and the OBA support points. Heavy components are mounted at junctions of several ribs. Lighter component attachment points are supported by rib extensions from primary ribs. The lightest components (such as baffles, harness tie downs and thermal straps) are not supported by ribs, but thread into a boss extending from the facesheet. Rib thicknesses are governed by load requirements (thicker ribs near support points). The minimum rib thickness is governed by manufacturability. Each rib has a T cross section which provides adequate bond area yet minimizes mass. The rib geometry is shown in Figure 3.

2.9 Venting Internal Volumes

Each pocket vents to each adjacent pocket by notches cut in tops of ribs. The internal volume vents to the exterior through threaded filter vents installed in side walls of the bench. Blind holes are vented to the interior volume. Some blind holes used only during ground integration and testing are not vented and components mounted in these holes must provide vented fasteners. This venting method prevents contamination from the lower cleanliness level interior of the bench from reaching the outside when the holes are not filled for flight.

2.10 Bond Details

The bond line thickness must be controlled to be between 153 and 305 microns. This is achieved by raised areas on rib junctions on both top and bottom half benches. Figure 4

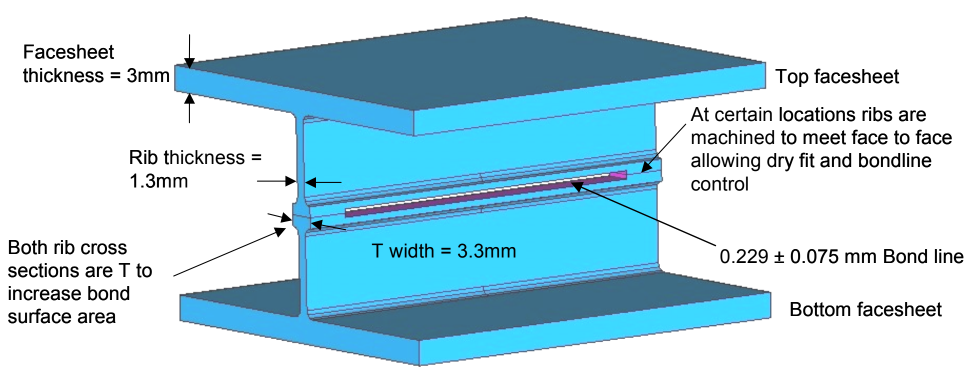

Figure 4: Bond line details

illustrates the bond line control features.

2.11 Doublers

In addition to the bond joint at the rib junction, Beryllium doubler plates are bonded to the side walls of the benches near each interface bracket. The plates span the height of the bench and serve to increase the strength of the joint in the high stress areas.

2.12 Component Attachments

Optical component mount points (3 per component) are raised above the top surface of the bench by 75 microns so that those areas can be more tightly controlled in profile. All raised areas also have better surface finish. Attachment bolt size is dependent on component mass. All optical components and mechanisms have match-drilled holes through the top and bottom half benches. Threads are in the bottom half bench, while a precision hole is in the top half bench. Custom precision bolts with their shaft diameters tightly controlled so that component shear load is transferred to the bench through the bolt shaft are precision fit to the top half bench hole. Nitronic 60 helicoils are used to prevent galling with either Titanium or stainless bolts. Smaller mass components like thermal straps, baffles, harness tie downs, and alignment tools have holes in only the top half bench. Bench holes require very tight diameter control and perpendicularity because any errors could lead directly to errors in true position of optics, which must comply with optical positional tolerance allocation. True position of the match-drilled holes with respect to datums is not as tight because the attachment method for components allows adjustability with the use of dual cams. Cam diameters and hole perpendicularity must be held very tightly as these errors could also contribute to optical position errors. Dual cams can be adjusted to provide either +/-0.5mm or +/-1.5mm of adjustment in the plane of the bench depending upon the component. In crowded areas adjustability is limited to +/-0.5mm. The vertical height of components can be adjusted through the use of shims between the bench surface and the component mount. Figure 5 depicts the component attachment method with shims and dual cams.

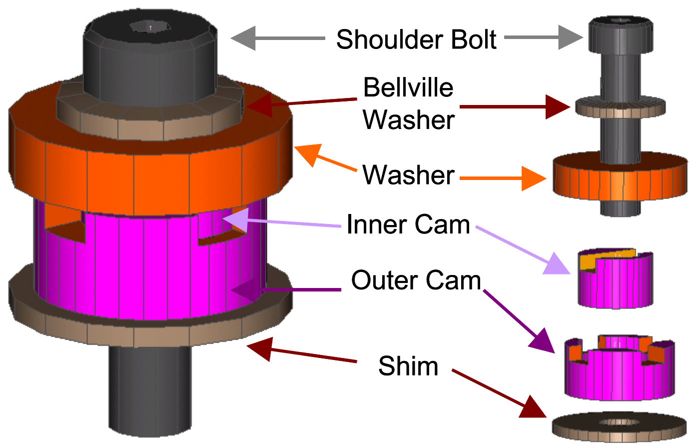

Figure 5: Component attachment method providing adjustability

All components will be mounted to the bench with flexures that allow for differential thermal contraction between the component material and the Beryllium bench. All component interfaces are Titanium, which has a greater change in dimension between room temperature and 35K than does Beryllium.

2.13 ISIM Attachment

After the bench modules are aligned back to back with pins and are bolted together, three brackets are bolted to both benches, which provide the interface to the JWST integrated science instrument module (ISIM). NIRCam is attached to the ISIM with 3 sets of bipods. Each bipod attaches to one of the brackets with 2 pins and 4 bolts. Figure 6 shows three interface brackets attached to the OBA and to the ISIM struts.

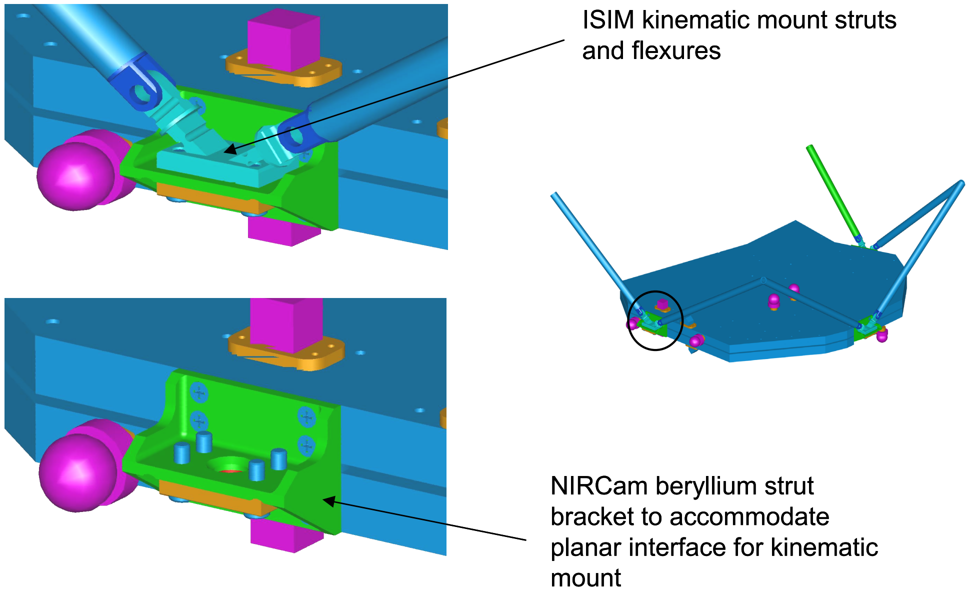

Figure 6: ISIM Interface brackets with struts attached

2.14 Surface Treatments

A study was done to determine the best surface preparation for bonding Beryllium. This study and the results are presented in a companion paper [1]. The study found that adequate bond strength could be obtained if the Beryllium surfaces were black anodized and then primed with BR127 epoxy primer. This treatment will be done on the rib side of each half bench.

A non-reflective, black surface is required for stray light reduction everywhere inside the optical train (beneath the baffles) and near the optical path. To meet this requirement the bench will be black anodized. A competing requirement was developed based on thermal needs. The exterior surfaces of the NIRCam instrument (those with a direct view to the ISIM) need to have a low emissivity surface. Black anodized surfaces do not meet this requirement. Therefore the surfaces not covered by the baffles and outside the direct light path will be left bare Beryllium, which does have the low emissivity required. These surfaces will be passivated so that the Beryllium will not oxidize.

3. ANALYSIS RESULTS

3.1 Warm to Cold Predictions

All of the NIRCam optical components must be installed and aligned at room temperature and come into alignment at the operating temperature of 35K. The optical prescription is defined at the operating temperature (35K). The positions of the optical components at room temperature must be predicted based on thermal dimensional changes of all components. First a zero expansion point of the OBA was determined based on the geometry of the ISIM interface struts. Warm and cold locations for the component mount points could be then be determined based on the predicted change in the bench size due to thermal contraction. Component mount points on the bench were established early in the design based on the cold prescription and preliminary component designs and were then treated as fixed points. This approach was required due to the long lead time for bench manufacturing. The warm optic geometries were determined by scaling the cold prescription geometries based on each optic material's dl/l property. (dl/l is measured experimentally and is the change in length over a prescribed temperature change divided by the original warm length). Finally the warm location of each optic is determined based on the predicted change in the bench, the component mount and the optic.

3.2 Structural Analysis

The optical bench stress and modal model was meshed in I-DEAS Master Series version 9 and exported through a translator for MSC/NASTRAN version 2001. Analysis runs and model checks were performed with NX/NASTRAN version 2.0.

The model is intended to capture the bench structure in detail with lesser detail for the individual optical components on the bench. The bench face skin and ribs are modeled as shell elements. Fastened and bonded connections between bench sub-elements are modeled with either finite length beam elements or zero length rigid elements. ISIM mounting brackets and some optical component mounting brackets are also modeled with shell elements. All optical components are mounted to the bench with semi-kinematic flexures which are modeled with beam elements. The optical components themselves are modeled as lumped mass elements with zero inertia. The components are connected to the bench with semi-rigid NASTRAN RBE3 elements. Figure 7 shows the finite element model.

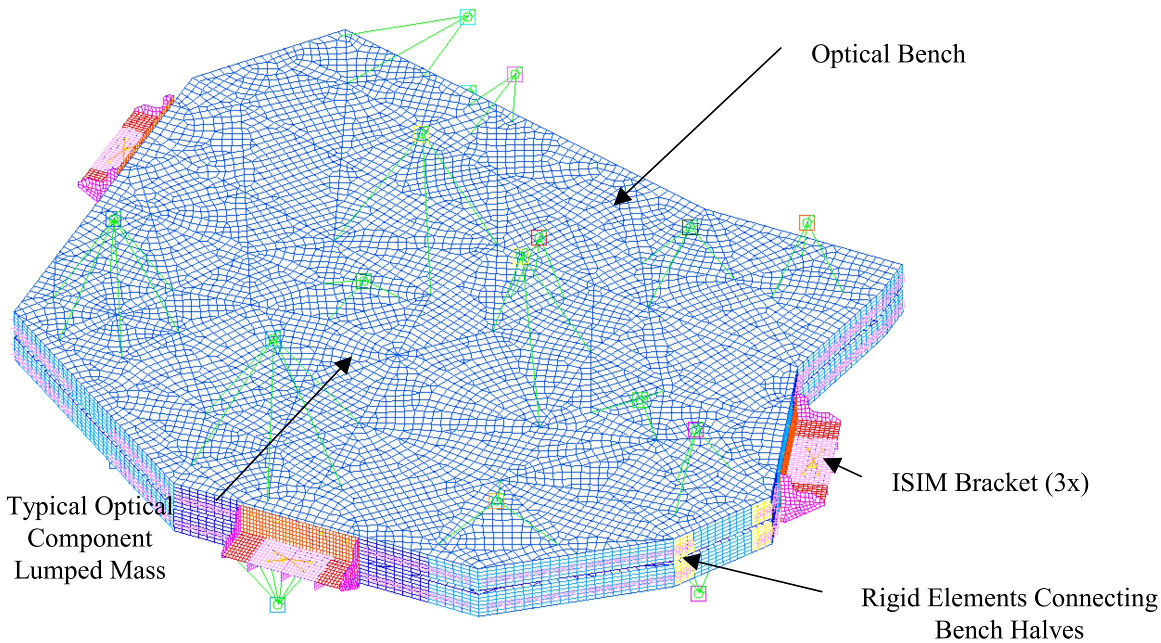

Figure 7: Optical Bench Assembly finite element model

The model attaches to the ISIM at three nodes. The boundary conditions degrees of freedom simulate the pseudo-kinematic degrees of freedom of the ISIM struts.

In addition to the overall OBA model, detailed stress models were also created. A detailed solid model of the ISIM bracket was created to capture detailed stresses for fracture analysis. A similar model was created for the bracket interface on the bench.

3.2.1 Stress Analysis

The optical bench is mostly stiffness driven, but there are localized areas where stresses are high. This is particularly the case for the external and internal interfaces for heavier components. Depending upon the material and failure mode, different safety factors are applied. The margin of safety is then calculated as follows:

Margin of Safety = [Allowable Load / (Safety Factor x Working Load)] – 1

A margin of safety greater than zero is required. The margins of safety are summarized in Table 1:

Table 1. Margin of Safety Summary

Component	Material	Failure Mode	Allowable	Working Load	Safety Factor	Margin of Safety
OBA Faceskins	I-220-H Beryllium	Tensile Fracture	135 MPa	36 MPa	1	2.75
OBA Ribs	I-220-H Beryllium	Tensile Fracture	95 MPa	58 MPa	1	0.64
OBA Faceskins	I-220-H Beryllium	Buckling	123 MPa	36 MPa	1.4	1.44
OBA Ribs	I-220-H Beryllium	Buckling	7516 MPa	58 MPa	1.4	91.56
OBA Ribs	I-220-H Beryllium	Shear Buckling	10330 MPa	34 MPa	1.4	216.02
OBA Solid Plugs	I-220-H Beryllium	Tensile Fracture	180 MPa	35 MPa	1	4.14
OBA Rib Bond	Epibond 1210	Peel	28 MPa	6 MPa	1.25	2.73
OBA Rib Bond	Epibond 1210	Shear	29 MPa	13 MPa	1.25	0.78
ISIM Bracket Center	I-220-H Beryllium	Tensile Fracture	160 MPa	57 MPa	1	1.81
ISIM Bracket Edge	I-220-H Beryllium	Tensile Fracture	130 MPa	37 MPa	1	2.51
ISIM Bracket Center Hole	I-220-H Beryllium	Tensile Fracture	210 MPa	156 MPa	1	0.35
ISIM Bracket Center Hole	I-220-H Beryllium	Bearing	345 MPa	123 MPa	1.4	1.00
OBA ISIM Bracket Interface Solid Plug	I-220-H Beryllium	Tensile Fracture	180 MPa	53 MPa	1	2.40
OBA ISIM Bracket	I-220-H Beryllium	Tensile Fracture	135 MPa	108 MPa	1	0.25
OBA ISIM Bracket	Epibond 1210	Peel	28 MPa	21 MPa	1.25	0.07
OBA ISIM Bracket	Epibond 1210	Shear	29 MPa	21 MPa	1.25	0.10
OBA Cam Inserts	I-220-H Beryllium	Compression	345 MPa	204 MPa	1.4	0.21
OBA Cam Inserts	I-220-H Beryllium	Compression	345 MPa	166 MPa	1.4	0.48
Component Fastener	6-AL-4V Titanium	Tension	931 MPa	511 MPa	1.67	0.09
ISIM Bracket Fasteners	6-AL-4V Titanium	Tension	931 MPa	151 MPa	1.67	2.69
Component Fastener	6-AL-4V Titanium	Shear	572 MPa	193 MPa	1.4	1.12
ISIM Bracket Fasteners	6-AL-4V Titanium	Shear	572 MPa	90 MPa	1.4	3.54
OBA Faceskins	I-220-H Beryllium	Fastener Bearing	345 MPa	170 MPa	1.4	0.45

Many of the Beryllium stress allowables take into account safe life fracture which will be discussed later.

Figure 8 shows bench surface stresses with a 12g load (the prescribed limit load per requirements) applied perpendicular to the bench surface. The figure illustrates the general distribution of stress and areas of peak stress.

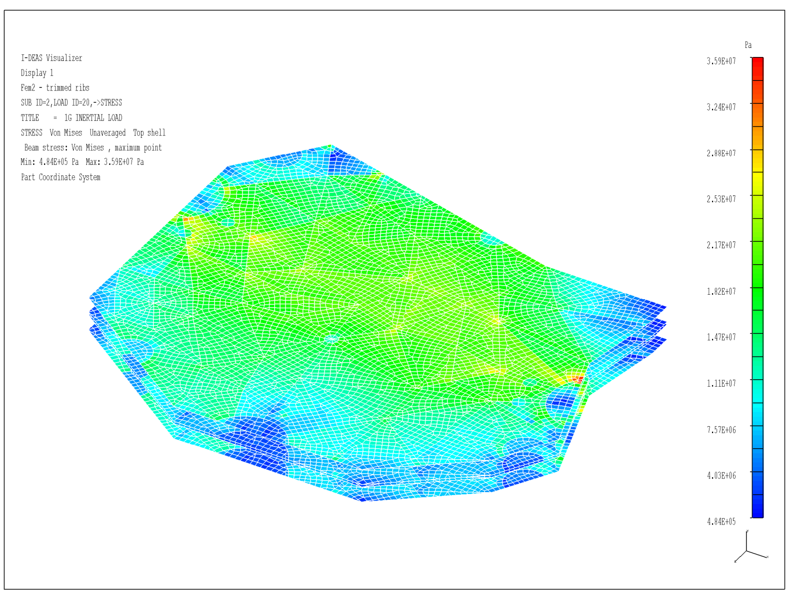

Figure 8: Bench Stresses peak at 36 MPa with a 12g Load applied Perpendicular to the Bench

3.2.2 Modal Analysis

The optical bench is required to be very stiff so that it does not couple with the spacecraft or launch vehicle primary modes during launch, which could generate high loads. The OBA must also be stiff under 1g loading during integration and testing of the optics so that the optics remain aligned once on orbit in a 0g environment.

The first mode is an out-of-plane mode at 86 Hz. The mode shape (greatly exaggerated) is shown in Figure 9.

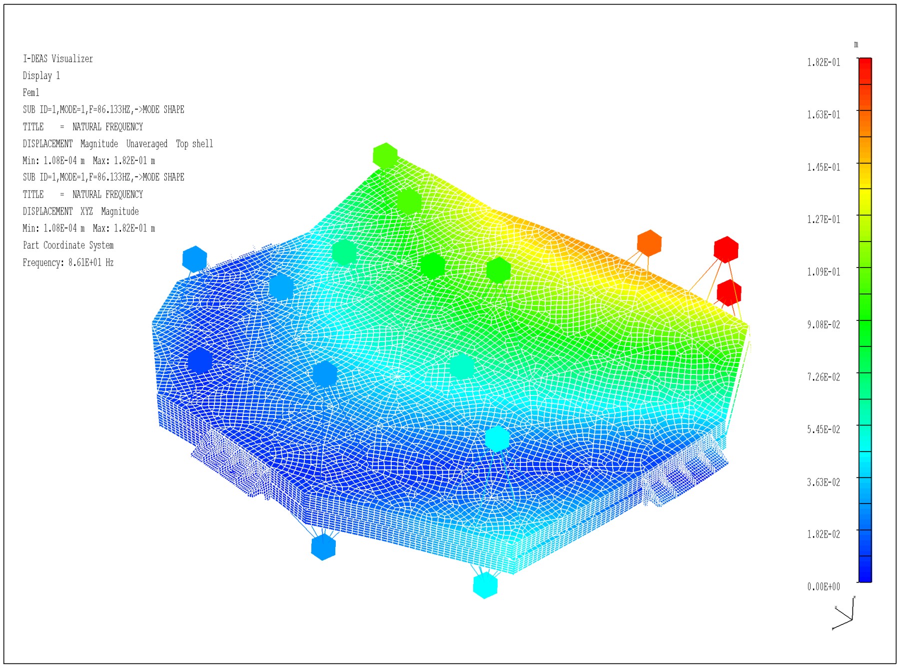

Figure 9: First Mode at 86 Hz (scale is greatly exaggerated)

3.2.3 Fracture Analysis

The bench is mostly designed for stiffness, but there are a few places where stresses are high and showing positive structural margins of safety was difficult. A small crack or flaw in one of these areas could grow over time as the area is loaded and unloaded and could grow large enough to fail the part. Brittle materials such as Beryllium require that a “safe life” analysis is performed if the part could affect flight safety or is mission critical. This analysis requires that a minimum detectable flaw does not grow large enough to fail over all the load cycles that the part will see in its lifetime. To add a margin of safety, this analysis is usually extended to 4 lifetimes since determining the exact number and magnitude of load cycles is difficult.

Equivalent design allowables for fracture were calculated with NASGRO 4.2a using the following approach. The design allowable was determined to be the maximum stress where the critical crack size has not been reached for 4 lifetimes of load cycles plus margin. Minimum detectable flaw sizes were assumed to be NASA standard flaw sizes for dye penetrant inspection as specified in NASGRO. Lastly, material properties for HIP’d S200E Beryllium in the NASGRO database were used where explicit properties or fracture parameters for I-220-H Beryllium were not available.

For sine vibration, the number of load cycles at peak load can be estimated by the product of the primary resonant frequency and the time spent at that frequency. From Steinberg, the time it takes to sweep through the half-power points can be determined by:

$$t = \frac{\log_e \dfrac{1+(1/2Q)}{1-(1/2Q)}}{R\log_e 2}$$

where t is time in minutes, R is the sweep rate in octaves per minute, and Q is the transmissibility at resonance.

For random vibration, the equivalent 1 sigma static load at peak resonance can be estimated with Mile's Equation. Using a three band technique from Steinberg, the time spent at the resonant frequency can be expressed as a percentage of the total random vibe test duration:

1 sigma stresses occur 68.3% of the time.
2 sigma stresses occur 27.1% of the time.
3 sigma stresses occur 4.33% of the time.

The most critical area for fracture is at the ISIM interface where large shear loads (17,000 N) are carried through a 12.7mm pin. Figure 10 shows the local stresses in this area.

A minimum detectable crack length of 1.27 mm was assumed using standard dye penetrant inspection. The 4x safe life allowable for this minimally detectable crack is 210 MPa. This results in a margin of safety of only 0.35. The 210 MPa fracture allowable is significantly below the 345 MPa yield strength for this material. In other areas of the bench, the fracture allowable is as low as 95 MPa. However, the stresses are also lower in those areas.

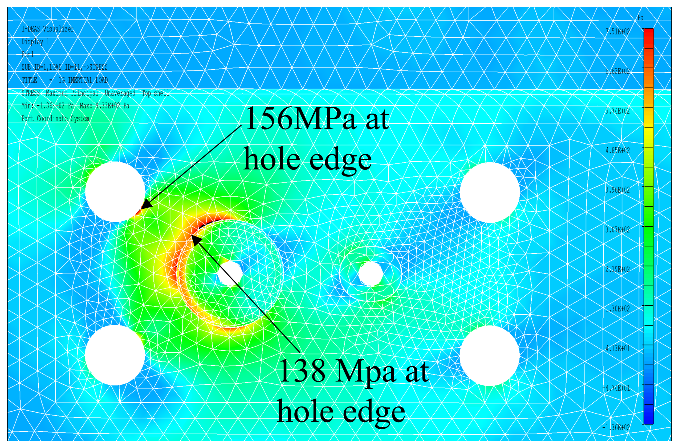

Figure 10: Local Stress with Left Lateral Load

4. CONCLUSION

The Optical Bench Assembly for the NIRCam instrument has been designed for optimal stiffness and mass while still providing for separability during integration and testing. The assembly is composed of two separate optical benches mounted back to back. Each optical bench is a closed back Beryllium structure bonded along its mid-plane. Manufacturability was strongly considered and built into the design. The design has been analyzed and shown to meet structural, dynamic and dimensional stability requirements. The Optical Bench Assembly will serve as the primary structure for the NIRCam instrument within the James Webb Space Telescope.

5. REFERENCES

[1] "Selection of I-220H Beryllium for the NIRCam Optical Bench", by Derek Edinger and Alison Nordt, SPIE 2005.