Large prism mounting to minimize rotation in Cassegrain instruments

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ABSTRACT

The Echellette Spectrograph and Imager (ESI), currently being developed for use at the Cassegrain focus of the Keck II 10-m telescope, employs two large (25 kg) prisms for cross dispersion. In order to maintain optical stability in the spectroscopic modes, these prisms must maintain a fixed angle relative to the nominal spectrograph optical axis under a variety of flexural and thermal loads. In this paper, we describe a novel concept for mounting large prisms that has been developed to address this issue. Analytical and finite element analyses (FEA) of the mounts are presented. Optical and mechanical tests are also described.

Keywords: Prism mounting, spectrographs, Cassegrain, space frames, cross-dispersing prisms

1. INTRODUCTION

Practical performance of modern spectroscopic instruments is driven in part by the stability of the individual optical components. Stability of these components can be affected by a variety of issues, including gravity or thermally-induced motions of the optical elements, stress induced deformations of the optical surfaces, and thermally-induced changes in the refractive index of in the materials making up the components.

As telescope apertures continue to increase, so must the aperture of the spectroscopic instruments if they are to maintain high spectroscopic and spatial resolution. In fact, for a fixed grating angle, fixed spectroscopic resolution and fixed angular slit size, the spectrograph aperture size must increase linearly with the telescope aperture.[1] The mass of the optics within these spectrographs will increase as the cube of the aperture. Simple scaling laws show that angles will increase linearly and displacements will increase quadratically with spectrograph size. Thus, the control of tilts and displacements of the optical components due to gravity-induced flexure becomes an increasingly difficult problem as telescope apertures increase.

Nowhere is this problem more apparent than for instruments mounted in the Cassegrain configuration. In most cases, the mechanical designer must contend with a variety of gravity induced flexures. These include motions of the individual optics and groups of elements, bulk motion of the entire instrument relative to the telescope and strains introduced into the instrument structure by flexure of the telescope mount itself.

One such instrument for which these issues are of great concern is the Echellette Spectrograph and Imager (ESI) shown in Figure 1. This is a multipurpose spectrograph currently being developed for the Cassegrain focus of Keck II telescope by the Instrument Development Lab at Lick Observatory. The ESI is a medium resolution spectrograph, utilizing two large (25 kg) prisms for cross dispersion. It has three scientific modes: a medium resolution Echellete mode, a low resolution prismatic mode, and a straight imaging mode. The spectrograph is described by Epps and Miller in these proceedings.[2]

In this paper, we present a solution to the flexure problem, as it applies to the mounting for the 25 kg cross dispersing prisms for the ESI spectrograph.

2. DESIGN PHILOSOPHY

The philosophy that has been developed at the University of California Observatories (UCO) to address the issue of flexure is illustrated by the design and analysis of the mounting system used for these cross dispersing prisms. This philosophy is characterized by the use of determinate structures or space frames wherever possible. A determinate structure connecting a rigid body to "the world", is one that constrains the six degrees of freedom of a solid body , i.e. exactly six degrees of freedom are constrained by six structural elements or struts connected to the "world" at six points or nodes. Up to three pairs of the nodes may be degenerate. Struts are used in compression and tension only. Thus, deflections of the struts are linear with length, as opposed to struts or plates used in bending where the deflections are proportional to the third power of the length. Other examples can be found in the description by Radovan et al. of the active collimator used for tilt correction of this instrument,[3] and in the description by Bigelow et al. of the space frame which provides the backbone for the entire instrument.[4]

The desirable features exhibited by this type of mounting arise because the struts carry only compressive or tensile loads. Lines of force between struts intersect at a single point or node. Thus, no moments can be imparted at the strut connections. In fact, joints are typically modeled as frictionless pin-joints to insure no moments are included in the design. The advantage of no moment carrying connections is that distortions of one object (i.e. an optical mounting surface) will causes a motion without inducing stresses in the mounted object (i.e. optical component). Similarly, distortions of the determinate structure, for example from a temperature gradient across the structure, cannot induce a stress in the optic, only displacements and rotations. The challenge to the designer is to create a determinant structure which allows only motions of the component that the optical system is tolerant of, and failing that, orchestrate the motions of combined groups of optics such that the combined set of errors are below that prescribed by the error budget. In this way the mechanical designer must work very closely with the optical designer to establish the predicted performance of the system prior to actual construction.

In the case of ESI, the designers have initially tried to minimize the product of the motion and the sensitivity for each component prior to considering the combined impact of motions of all components on the image blur. In the following sections we describe the design procedure used to limit the motions of the ESI cross dispersing prisms to an acceptable level.

3. DESIGN REQUIREMENTS

The cross dispersing prisms are in collimated light; therefore to first order, small translations of the prisms will produce pupil motion only and no corresponding image motion. Tilts of the prisms will produce any combination of the following: image motion, change of the cross dispersion direction, change in the amount of cross dispersion, change in the anamorphic factor, and increased distortion. Therefore, the most important stability criteria for the prisms is control of tip and tilt, with almost no requirement on displacement stability. If all these factors are taken into account, the sensitivities as worked out by the optical designer (Sutin, private communication) for ESI, are ±0.013, ±0.0045, and ±0.014 arcseconds of image motion for ±1 arcsecond of prism tilt about the X, Y, and Z axes, respectively, where X, Y, and Z, are local coordinates as shown in Figure 2b. The desired spectrograph performance is ±0.06 arcseconds of image motion without flexure control and ±0.03 arcseconds of image motion with flexure control for a two hour integration. For a reasonable choice of the allowable percentage of the total error allotted to the prism motion, these sensitivities give a requirement of less than ±1.0, ±2.0 and ±1.0 arcseconds rotation about the X, Y and Z axes.

In addition, careful attention must be paid to the induced stresses in the glass. Not only must one be concerned with the potential for fracture of the glue (or worse the glass), but stress induced in the glass will cause a corresponding local change in the index of refraction of the glass, causing a possible wavefront distortion. In order to insure against glass breakage, we have allowed for up to 2% of the yield stress of the glass to be imparted at the glue joint under normal operation. If this criterion is used, attention must be paid to conditions that could induce more than 1 g acceleration into the glass, i.e. shipping, earthquakes, drive errors, collisions of the telescope with inanimate objects in the dome (e.g. cranes).

Several other equally important requirements of the mount design are: 1) minimization of measurable hysteresis, as hysteresis level limits the accuracy of the open loop flexure control system[3]; 2) ability to make a one time alignment adjustment of the prism tilts over a 30 arcminute range, during the initial assembly; 3) removability of the prisms for recoating, with a repeatable alignment position upon reassembly.

The normal operating temperature range for Keck instruments is $2\pm4^\circ$ C, and the total range seen at the summit is -15 to 20° C. The instrument must maintain all the above translational and rotational specifications over the entire working temperature range. Therefore the prism mounts need to be designed to be athermal with respect to tilts over this working temperature range and must keep stresses below the acceptable limits over the complete temperature range of the site (plus any extremes seen in shipping).

Additional, desirable design features for the prism mount system would include the handling fixture, light baffling and earthquake protection in the mounting scheme.

4. DESIGN DETAILS

In general our approach is to hold optics with determinate space frames and to interconnect optical assemblies with space frames. However, because of its complexity, it was found to be easier to build an optical substructure (OSS) as a bolted plate structure. The OSS is the central structure upon which all of the optical elements and assemblies, except the collimator, is attached.

The prisms are attached to the OSS with a determinate space frame consisting of 6 struts. Several geometries were explored. The attachment to the prism consists of two parts: a pad which is permanently glued to the prism; and a mating, detachable part which is permanently attached to the end of the struts. This allows the prism to be readily and repeatably installed and removed from its determinate support system.

Each prism mount geometry was first evaluated with a half-size foam core, hot melt and aluminum welding rod model for gross stability. These models were surprisingly useful during the early stages of the spectrograph development to quickly determine if we were on the right track or not. The next stage in the development was to produce a Finite Element Analysis (FEA) model of the structure, to determine the stiffness under varying gravity loads. Several stable configurations were developed using this technique. The final design was chosen based on the space constraints imparted by optical beam path and by the other optical components. Extensive use of solid modeling in AutoCAD was employed for the last phase.

The final design is pictured in Figures 2a and 2b. It is a six strutted, determinate structure that is mounted to the prism in one point on each of the three unilluminated faces via a bonded Tantalum pad. The thermal expansion coefficient of Tantalum closely matches that the BK-7 prisms. The structure mounts to a translation stage on the OSS in four locations through a bolted spherical washer. Each prism mounting location and two of the four OSS locations are degenerate pairs, with two struts connecting to a single node. Initial adjustment is provided by shimming the bolted connection points on the OSS.

Figures 3a, 3b and 3c show the FEA output of the preferred mount geometry of the mount at three different gravity orientations. In order to minimize rotation, the connection points of the struts were chosen such that the loading of each strut for a given gravity orientation was proportion to the effective compressive stiffness of each strut, thereby inducing equal displacements in each strut. This results primarily in translation, with a minimum of rotation. The final rotations due to gravity as determined by the FEA are given in Table 1.

Table 1. Rotations due to gravity

Gravity direction	Rotation about X (arcsec)	Rotation about Y (arcsec)	Rotation about Z (arcsec)
X	0.00	0.59	0.00
Y	0.56	0.00	0.00
Z	0.00	0.15	0.19

Each pair of struts is milled from a single piece of ground steel stock. Since each strut needs to constrain exactly one degree of freedom of the prism, crossed flexures were cut into each end of each strut to remove four degrees of freedom (one rotational and one translational per flexure pair). The fifth degree of freedom, axial rotation, is removed by the low torsional stiffness of the strut/flexure combination.

Flexure thicknesses and lengths were designed to impart less stress than the self weight loading of the prism into the prism pad connection and to be below the elastic limit over the full range of adjustment, while keeping the strut as stiff as possible. Strut thickness calculations and FEA are described in Appendix A. Pad areas were chosen to give a self weight induced stress of 125 KPa. If we consider the tensile strength of glass to be 7 Mpa,[5] this give a safety factor of 50. Tantalum was chosen for the pad material in an attempt to match the coefficient of thermal expansion (CTE) of the pad to that of BK-7 (the prism material). The CTE of Tantalum is $6.5 \times 10^{-6}/^{\circ}$ C versus BK-7 which is $7.1 \times 10^{-6}/^{\circ}$ C. Glue thickness and type was chosen based on the work of Iraninejad et al. (Ref. 6) during development of the glue connections for the Keck primary. In this work they found the thickness that minimized transmitted stresses in the glass while gluing Zerodur to Invar. In that case, Zerodur to Invar had a closer match of

CTEs than Tantalum to BK-7, so extensive stress testing over various temperature ranges was performed for BK-7 to Tantalum. This is described in § 6.

Figure 4 shows a schematic diagram of the strut geometry at two different, uniform temperatures. The advantage of the chosen geometry is that the prism translates under temperature variations rather than rotating.

5. ASSEMBLY

The assembly procedure for these prisms is as follows:

1. preassemble prism mounts on bench
2. install aluminium dummy prisms
3. drill and pin mounts to translation stage
4. remove dummy and mount
5. install glass prism onto spacers on the bench
6. reinstall mounts loosely and use metrology to locate prisms
7. tighten mounts
8. inject epoxy between pad and prism and let cure
9. remove prism with it's pads
10. install mount and translation stage into OSS
11. reinstall prisms

6. TESTS

Two areas of the development required extensive physical testing to confirm the predicted performance.

6.1. Glue Test

Although the optical impact of thermal and flexural stresses was modeled, we decided that due to the high technical risk involved, a mechanical test of the integrity of the glue joints and their assembly procedure was required; this is shown in Figure 5. Several samples of BK-7 were fabricated with the same type of surface specified on the prisms. These were bonded to either Tantalum or steel pads mechanically similar to the actual bonding pads for the prism mounts. These assemblies were subjected to tensile and sheer loads up to 10 times the expected loading in the instrument. The test jigs were then cycled 20 to 30 times over the expected temperature range of the Mauna Kea summit. None failed. The joints were then examined for stress birefringence under crossed polarizers. The level of wavefront error was calculated to be less than the limit prescribed by the error budget in the case of the Tantalum pad, but not for the steel pad. We therefore chose to use the Tantalum material for the bonding pad.

6.2. Stability Test

The actual mounting assembly was tested for flexural stability under varying gravity loads. Dummy prisms were fabricated by casting concrete into a welded aluminum model of the prism. The testing dummies matched the actual prism mass to 10% and the physical dimensions to 1%. These models were then assembled into the actual prism mounts then attached to a rotating platform. The rotating platform allowed us to continuously vary the gravity direction over 4π steradians. Rotations and translations of the dummy set were measured via a set of Linear Variable Differential Transformers (LVDT).

7. CONCLUSION

We have presented the design and analysis of the mounting system for the cross dispersing prisms for the ESI. In this design we have used the concept of a determinate structure whose members are in tension and compression only and impart no moments to the prisms. By careful consideration of the geometry, we were able to balance the loading at each strut for the three gravity orientations. This enabled the prisms to primarily translate under gravity, rather than rotate. Thermal stresses were minimized by careful material selection at the prism/metal interface. Careful selection of the geometry and materials also allowed for translations only with uniform temperature changes.

APPENDIX A. STRUT AND FLEXURE ANALYSIS

Flexure thickness was determined based on a $\pm\frac{1}{2}$ degree range of adjustment needed for the initial installation of the prisms. Over this range, we require less than 50% of the gravitational loading induced stress to be imparted into the glass. The initial analysis was based on hand calculations of induced bending moment versus flexure geometry as per Ref 5. After approximate thickness and lengths were determined, an FEA model was built for in depth analyses of the flexures. The FEA model was used to measure torsional and angular stiffness of the assembly, and to measure internal stress in the flexures at the limits of adjustment. The results of this analysis are pictured in Figures 6a and 6b, which shows the stresses at $\pm\frac{1}{2}$ degree of adjustment, the full range of the initial prism adjustment.

ACKNOWLEDGMENTS

The authors wish to thank Carol Osborne and Mary Poteete for their help with the design and drafting of many of the figures for this paper. Also, we would like to thank Harland Epps and Bruce Bigelow for their many helpful comments; Jim Ward, Jeff Lewis and Gary Dorst for their help in fabricating the tests and the actual mounting assemblies. Lastly we would like to thank Jack Osborne for his comments, criticisms and endless supply of gadgets.

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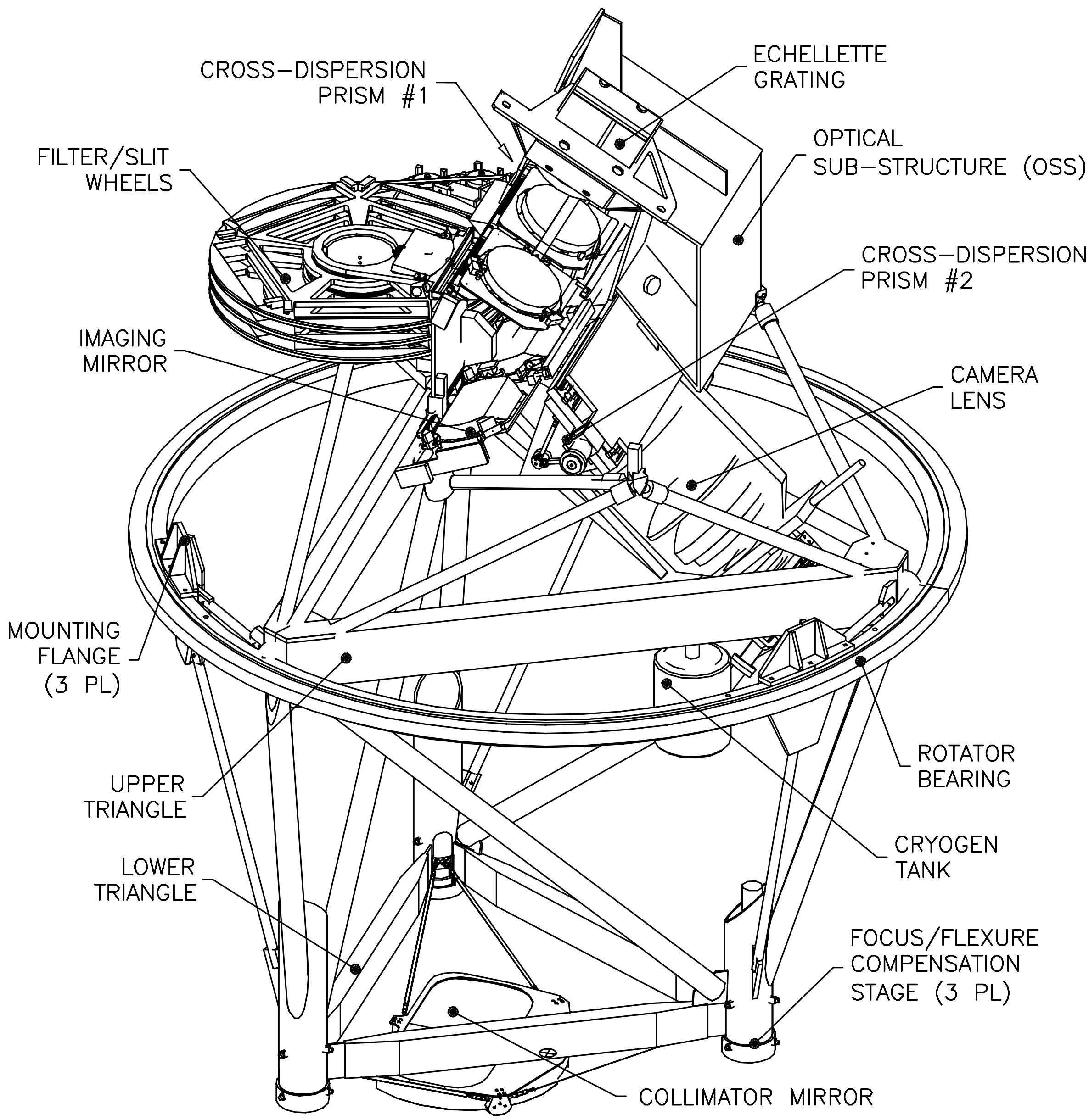

Figure 1. Echellette spectrograph and imager.

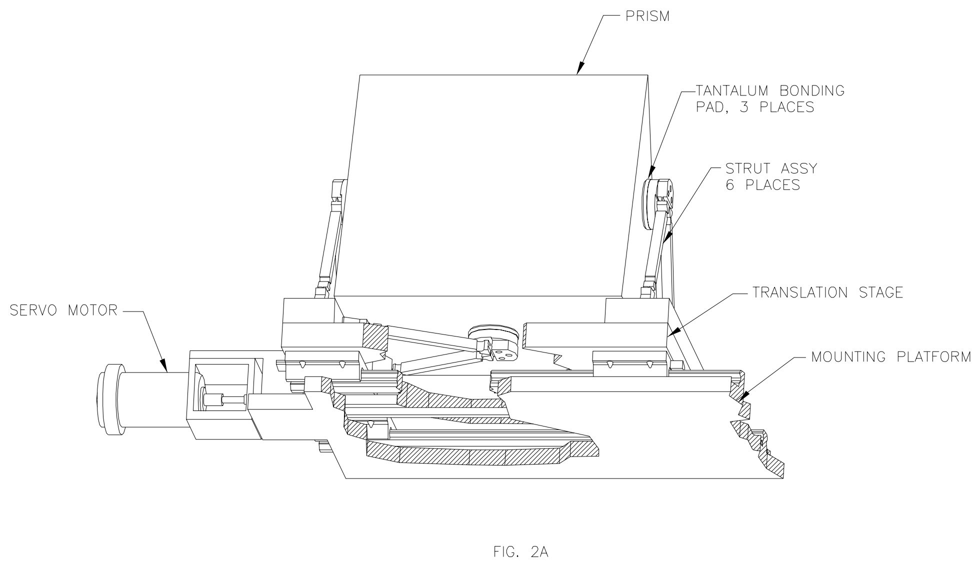

Figure 2. (a) Moving prism assembly.

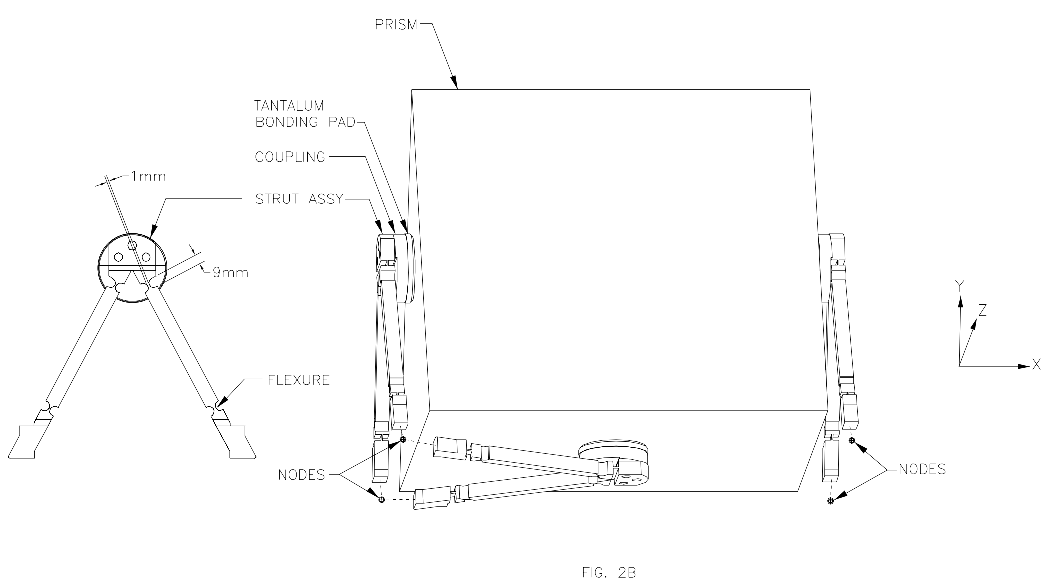

Figure 2. (b) Moving prism, mounting details.

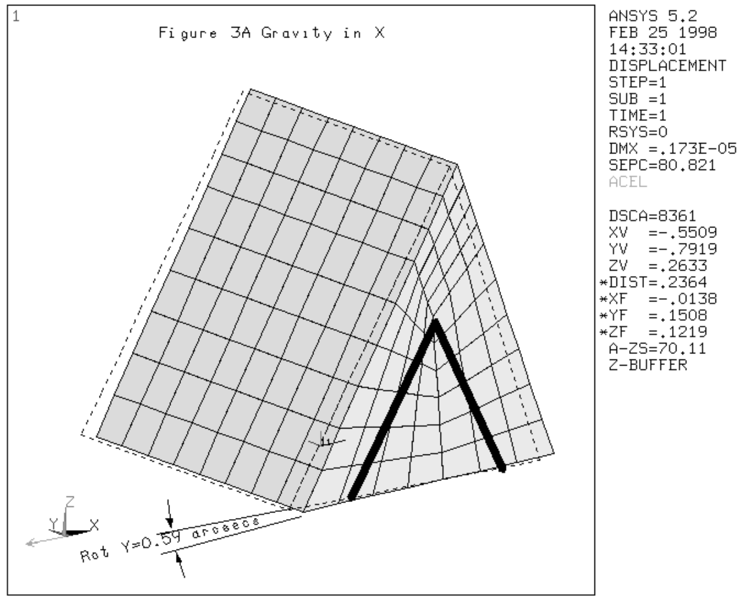

Figure 3. (a) Displacement output of FEA for gravity in X.

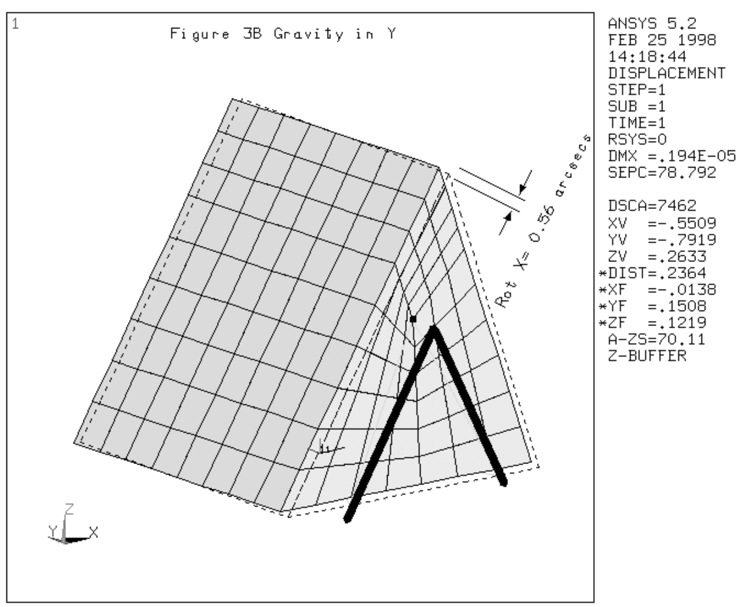

Figure 3. (b) Displacement output of FEA for gravity in Y.

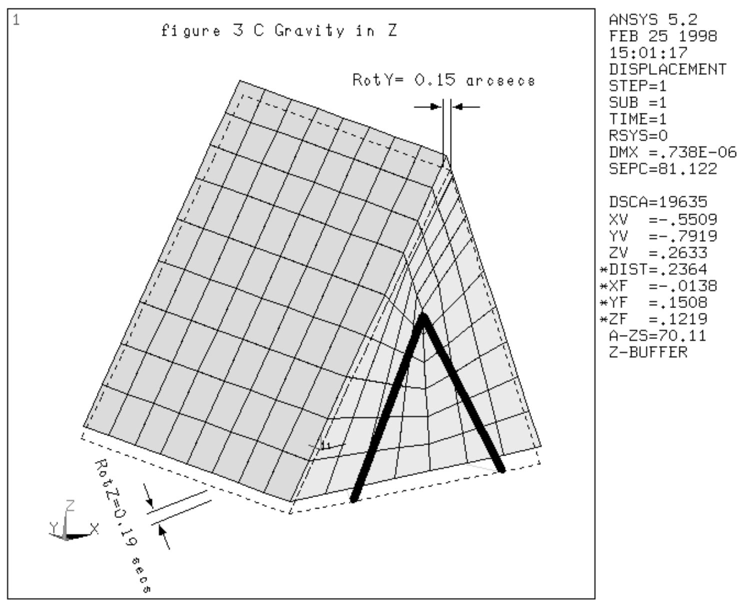

Figure 3. (c) Displacement output of FEA for gravity in Z.

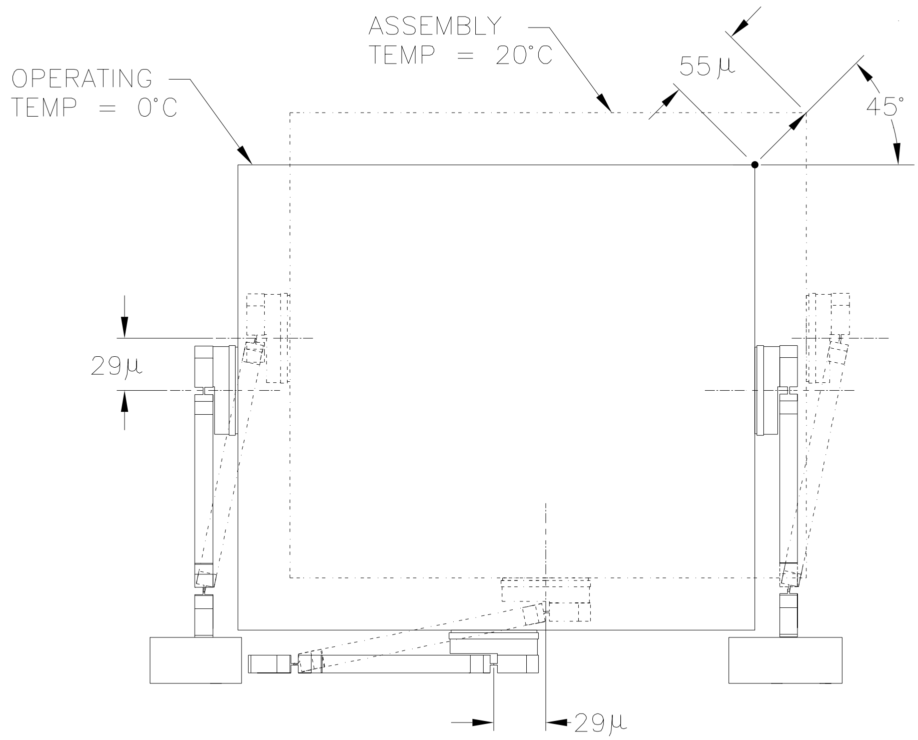

FIG. 4 PRISM ASSEMBLY AT
TWO TEMPERATURES

Figure 4.

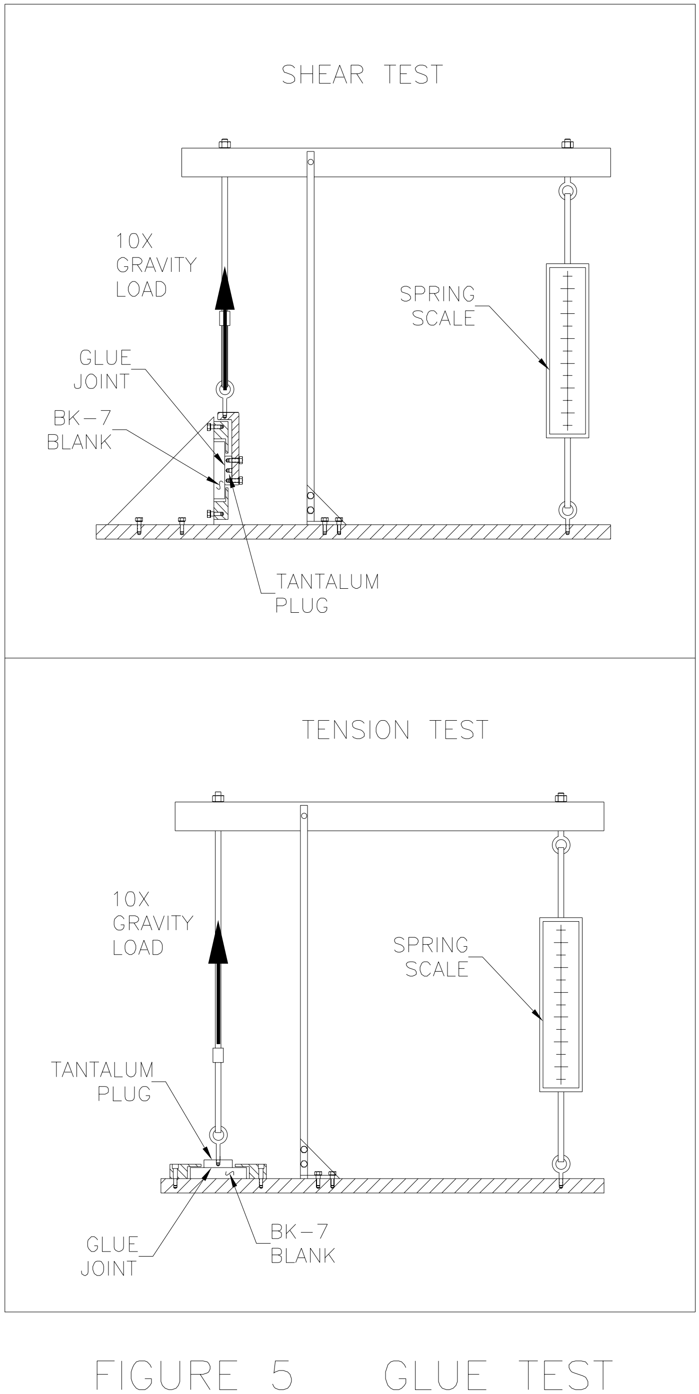

Figure 5. Shear and tension tests of prism-to-bonding pad glue joint.

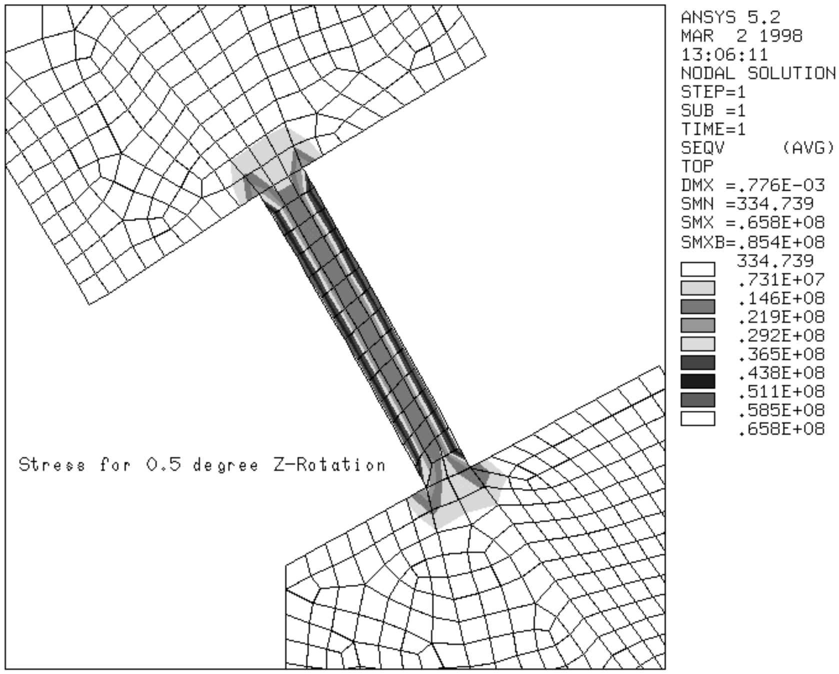

Figure 6. (a) Stress output from FEA of prism mount flexure (stress in Pa).

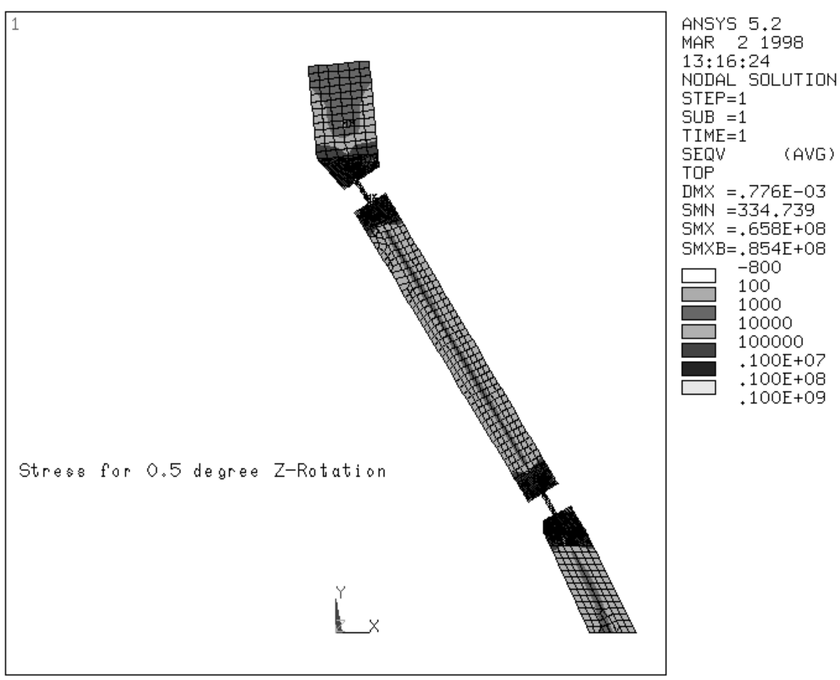

Figure 6. (b) Stress output from FEA of prism strut (stress in Pa).