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Project: Designing a Three and Four-Point Bending Load Frame for X-Ray Diffraction Experiments

Abstract:

A load frame capable of performing flexural testing was designed for use in High Energy X-Ray Diffraction (HEXD) experiments at the Cornell High Energy Synchrotron Source (CHESS). This load frame is the fifth generation of a compact, screw-driven load frame designed specifically for use at a synchrotron light source. It is designed to perform three and four-point bending flexural tests with a high level of precision. Alignment, calibration, and frame stiffness were considered to achieve this precision. These goals were implemented through the use of dual load cells, an alignment fixture, a saddle fixture, and a stiff frame.

Introduction:

HEXD techniques are used to nondestructively measure the strain within a sample. From these strain measurements, stresses are then calculated using Hooke's Law. To better understand the changing internal stress of a material undergoing deformation, HEXD experiments are often performed in-situ.[1] At CHESS, existing load frames, used for HEXD mechanical tests, were designed for testing samples subjected to uniaxial tension/compression or cyclic fatigue. These current load frames are not well suited to perform flexural bending tests effectively.

Flexural bending tests, including three and four-point bending, are methods for creating a stress gradient in a sample for the purpose of validating known models via experimental measurement. In three-point bending, load is applied at a single point of contact inducing both shear and bending stresses. In a four-point bending test, two rollers are used to apply load, with the purpose of inducing solely a bending moment in the sample. This creates a pure bending condition between the rollers; both cases are demonstrated in *Figure 1*.

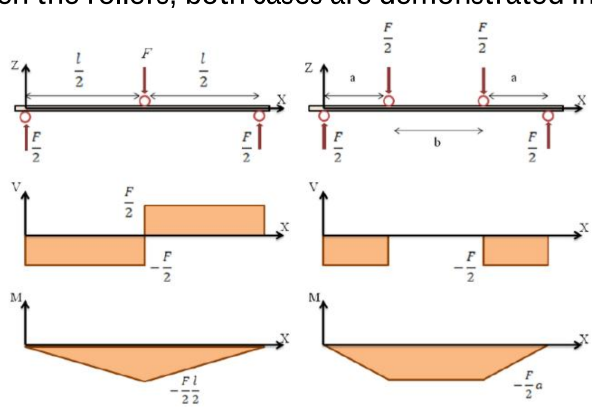


Figure 1: Three and Four Point Bending Shear and Moment Diagram[2]

Finite element analysis software can be utilized to model the simple cases previously mentioned as well as more complex sample geometries. The Finite Element Analysis software, ABAQUS (ABAQUS/CAE Student Edition 2017, Dassault Systemes, France), was used to model the loading cases of unnotched and notched titanium beams experiencing a couple moment, shown in *Figure 2*. The model was validated through hand calculations with an average percent accuracy of 1.36. The goal of this analysis was to model the deflection of a beam and track points of interest as a function of applied load. Points of interest were generated from the nodal coordinates of the finite element mesh and were measured using HEXD. This technique allows the points of interest to be measured while their location in space is changing.

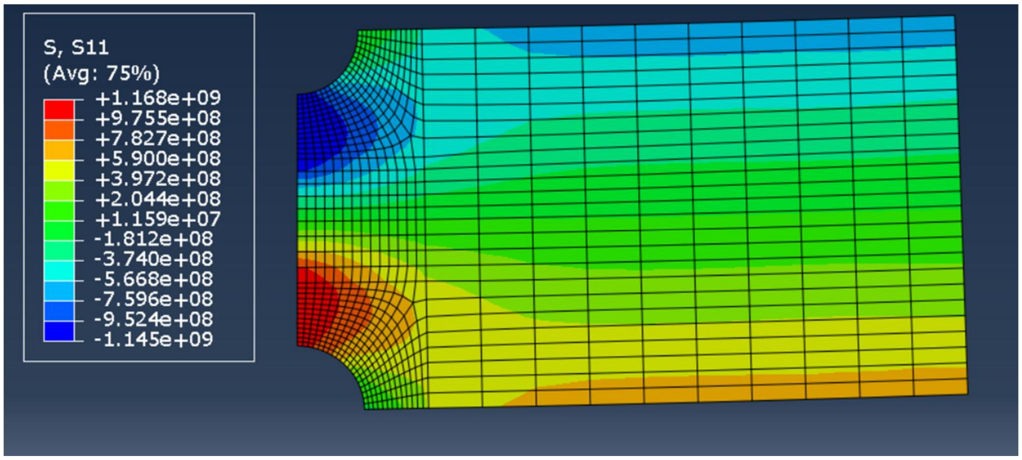


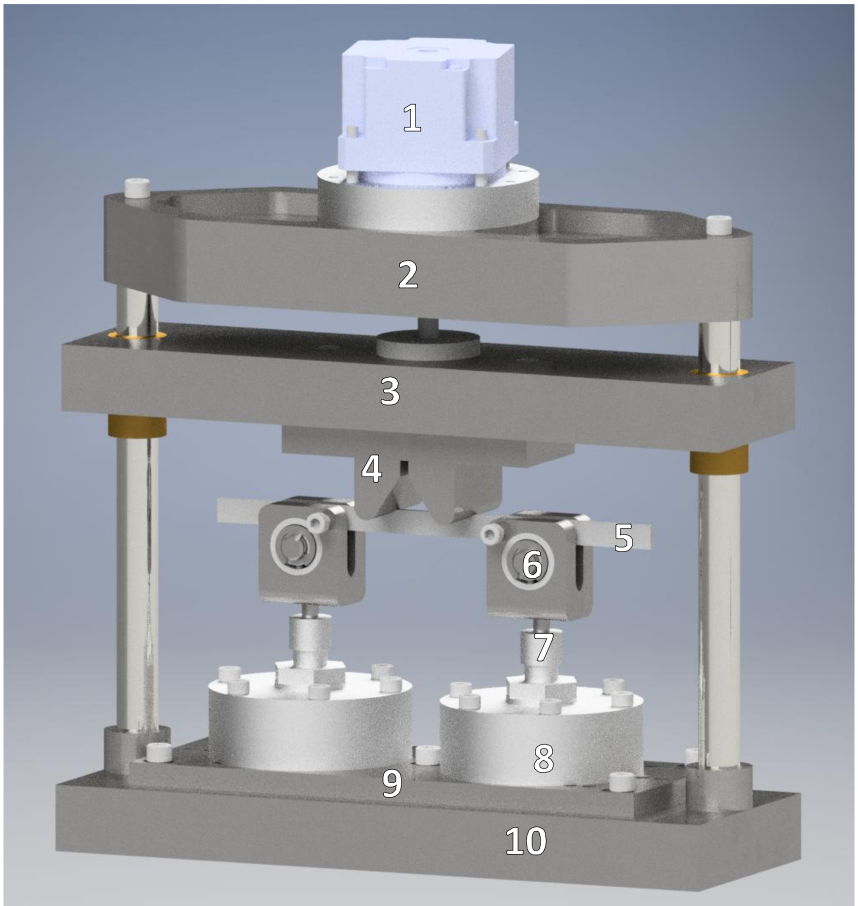
Figure 2: ABAQUS Model Showing Projected Deflection and Stress Gradient

When testing the specimens in four-point bending, numerous setbacks arose with the current load frame setting limitations on the data collected. These sources of error came from failure in specimen alignment, machine calibration, and control errors during testing. The new load frame design will focus on improvements in these areas.

Design:

The load frame design is to be compact, portable, stiff, and support both three and four-point bending while allowing an X-ray beam to penetrate the sample. The design of this load frame was modeled after a previous screw driven load frame with significant changes that affect alignment, including an additional load cell and bottom load cell plate.[3] This combination ensures that the sample is aligned within the frame correctly. The new load frame is modular and supports multiple configurations, where different configurations provide either a three or four-point bending test. Finally, the specimen being tested must stay aligned in three directions during loading and have adjustable roller placement to allow for various specimen lengths, depths, and thicknesses. A bottom roller mechanism is utilized for this purpose.

The final design, as shown in *Figure 3*, will have a total height, length, and width of approximately 12.11 inches, 10.75 inches, and 3.75 inches respectively. The main components of the load frame include the following: *top* and *bottom plates, crosshead, bottom load cell plate*, *motor, load cells,* and *support* and *loading rollers.*



1- Motor
2- Top Plate
3- Crosshead
4- Loading Rollers
5- Sample
6- Support Rollers/ Saddle Fixture
7- Collets
8- Load Cells
9- Bottom Load Cell Plate
10- Bottom Plate

Figure 3: Front View of Load Frame Design

The sample specifications and load frame interface, the support and load rollers, comply with guidelines from the American Society for Testing and Materials (ASTM). The rollers are ⅜ inch steel pins, which conforms with suggestions by ASTM. Beams of six, seven, and eight millimeter depths are supported with the lengths being determined by the same guidelines. The distance between the bottom rollers is sixteen times larger than the depth of the specimen with a ten percent overhang on both sides to determine the length. The thickness of the sample is three millimeters. ASTM specifies two top roller spacings. First, for measuring the strength of the specimen, quarter spacing is used because of its larger deflection; the second is third spacing which measures the modulus of the specimen. [4] *Figure 4* shows the distinction between quarter and third spacing.

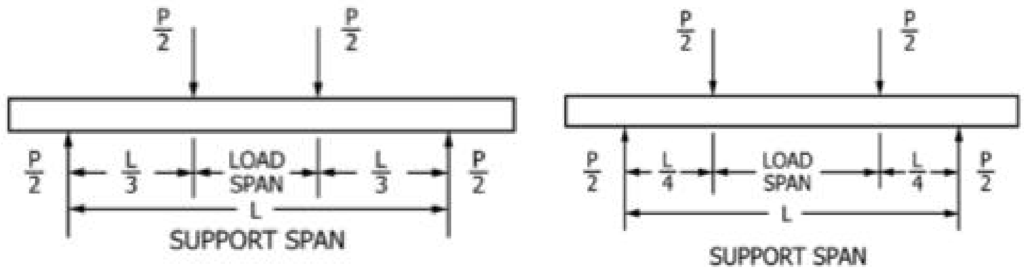


Figure 4: Third and Quarter Spacing for Four-Point Bending[4]

Loading rollers were designed to be adjustable to support both quarter and third spacing for each specimen depth and are aligned by alignment pins, as shown in *Figure 5*. *Table 1* shows the dimensions of supported specimens and the roller spacing. The design focuses on modularity for both sample size and test variables, both meeting design requirements and improving upon the previous design.

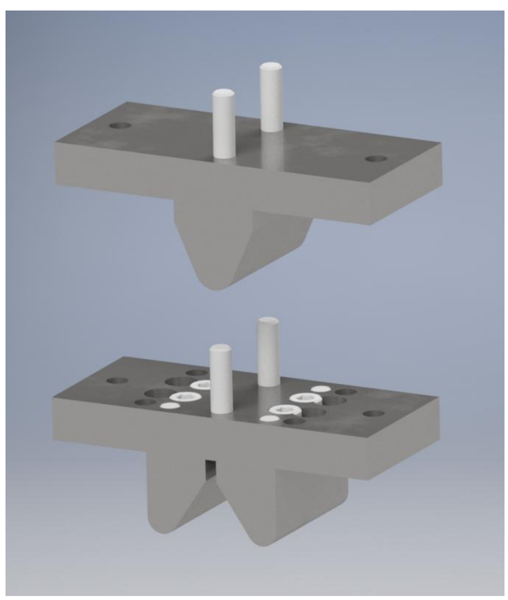


Figure 5: Crosshead Adapters for Three and Four-Point Bending

Table 1: Supported Sample Sizes and Matching Roller Distances in Millimeters

Sample		Support Roller Distance	Load Roller Distance	Load Roller Distance
Depth	Length		(1/3 Spacing)	(1/4 Spacing)
6	120	96	32	48
7	140	112	37 1/3	56
8	160	128	42 2/3	64

When designing the top plate, bottom plate, and crosshead for the load frame, deflection and stiffness were calculated and compared to the previous load frames used by CHESS. The load frame must have a high stiffness in order to minimize compliance of the load frame during testing. The existing compact load frames that inspired this project had a deflection at maximum load of approximately 0.0014 inches. This load frame has a deflection of less than 0.001 inches.

With the increase in span, a thicker top plate is required to keep the flexural deflection to approximately 0.001 inch. To ensure adequate stiffness and minimize deflection, the top plate was recessed to fit the motor while still keeping the load frame compact, shown in *Figure 6*. This design has a built in circular attachment on the top plate for the motor to bolt to and alignment pins to align the drive screw. When determining the thickness of the crosshead and bottom plates, the stiffness and deflection were calculated to meet the same standard of 0.001 inches with an actual value of 0.001 and 0.00068. An additional bottom plate is added to increase stiffness as well as for ease of alignment of the load cells.

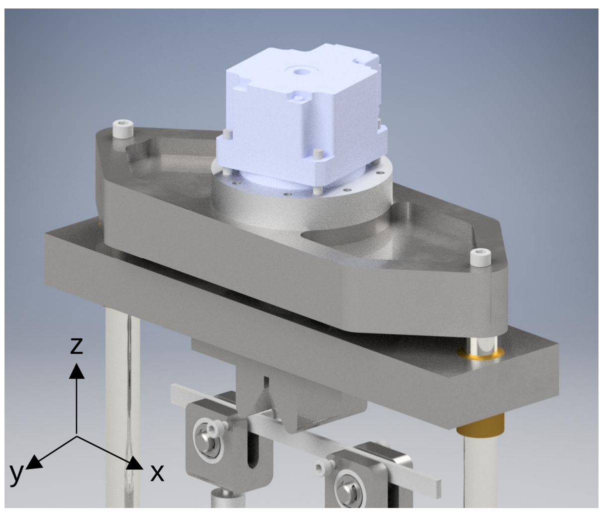


Figure 6: Top Plate Design

To keep the specimen aligned along every axis during loading, saddle fixtures hold the bottom of the specimen. The saddles are built around the supporting rollers which sit inside bearings to alleviate friction. Nylon tipped screws are used for adjustable alignment along the y-axis, shown in *Figure 7*. This fixture aids in creating a pure bending moment and prevents the specimen from slipping.

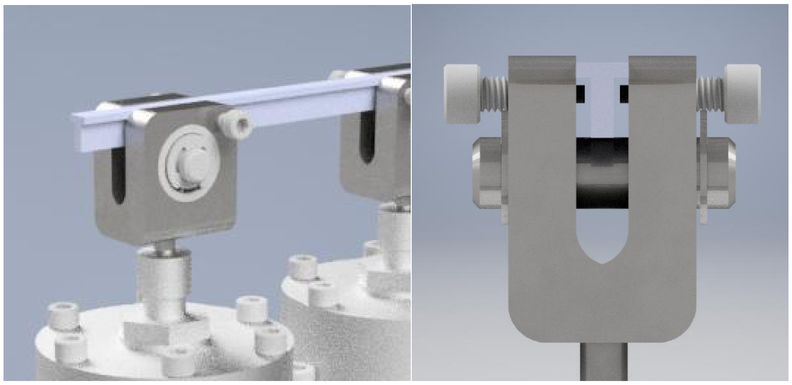


Figure 7: Bottom Roller Saddle Fixture

With accuracy in mind, the design has multiple alignment fixtures. The first fixture aims to align the load cells to each other and to the crosshead, shown in *Figure 8*. This ensures a pure bending moment by applying equal amounts of force on the specimen at a specified location. This initially aligns the load cells to each other using the bottom load cell plate and finally to the crosshead through alignment pins with three settings for varying specimen lengths.

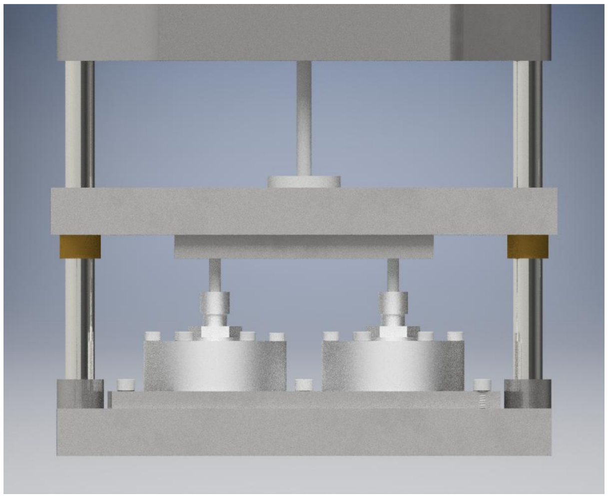


Figure 8: Device and Load Cell Alignment Fixture

The second alignment fixture is used both to align the support rollers to each other and set the nylon tipped screws in place for proper sample loading, shown in *Figure 9.* The top of the fixture precisely fits between the two inner faces of the saddle with the bottom thickness varying depending on the desired sample size. Once the fixture is set, the collets holding the saddle are tightened to ensure alignment during testing. Once aligned, the fixture is replaced with the specimen that will be tested. To align the specimen along the x-axis, the output from the load cells are read, showing the sample is centered.

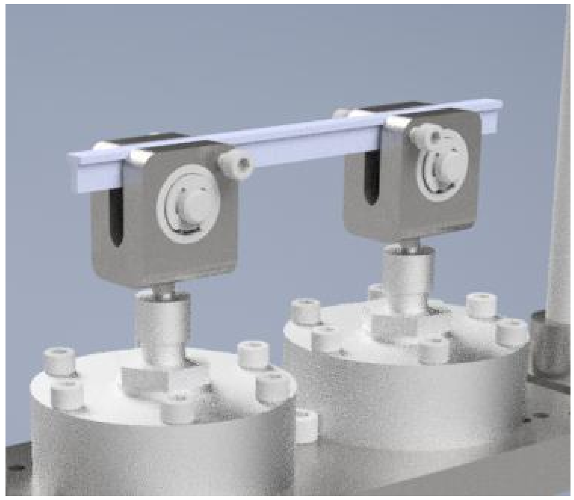


Figure 9: Sample Alignment Fixture

Detailed drawings and dimensions can be found in *Appendix A* along with a full materials list and detailed alignment procedure in *Appendix B* and *C.*

Conclusion:

Compared with current four-point bending methods used at CHESS, the dedicated flexural load frame proposed in this project should provide improvements in both precision and accuracy. This is anticipated due to the incorporation of multiple alignment devices, an additional load cell, and a sophisticated sample holder into the new design. The load frame supports both three and four-point bending for multiple specimen lengths and prevents shadowing for HEXD experiments while the overall design is modular for both sample size and test methods, varying from the previous designs. A final device is projected to be built in the fall of 2017.

References:

[1]B. Fultz, J. Howe. "Diffraction and the X-Ray Powder Diffractometer." *Transmission Electron Microscopy and Diffractometry of Materials*. Graduate Texts in Physics, DOI 10.1007/978-3-642-29761-8_1, © Springer-Verlag Berlin Heidelberg 2013.

[2]"Shear and Flexural Testing." *Objectives_template*. MHRD, Web. 27 July 2017. Image.

[3] Obstalecki, Mark. *Load Frame Mark 3, 4*. 2014, 2015, Cornell University, Ithaca, NY. Stainless steel load frame.

[4]ASTM Designation: D6272 – 17. “Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending”. ASTM International, West Conshohocken, PA.

Acknowledgments:

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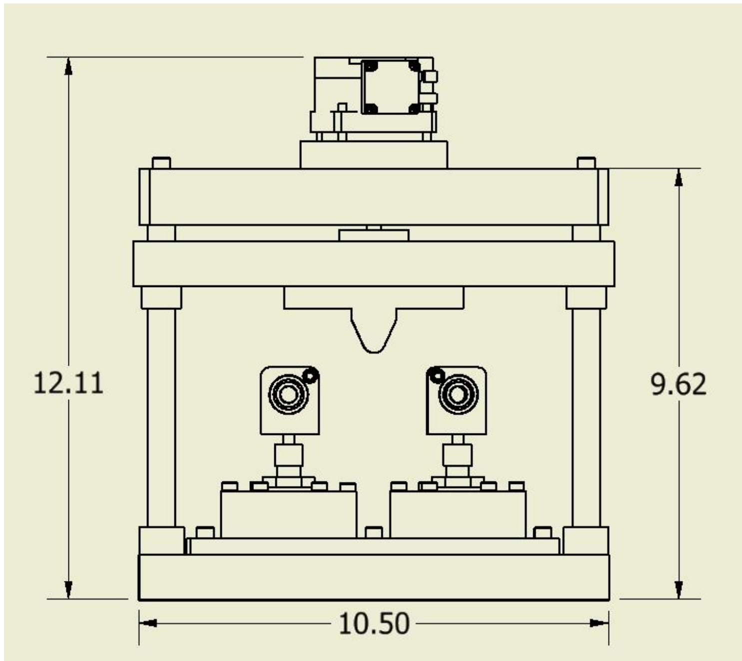
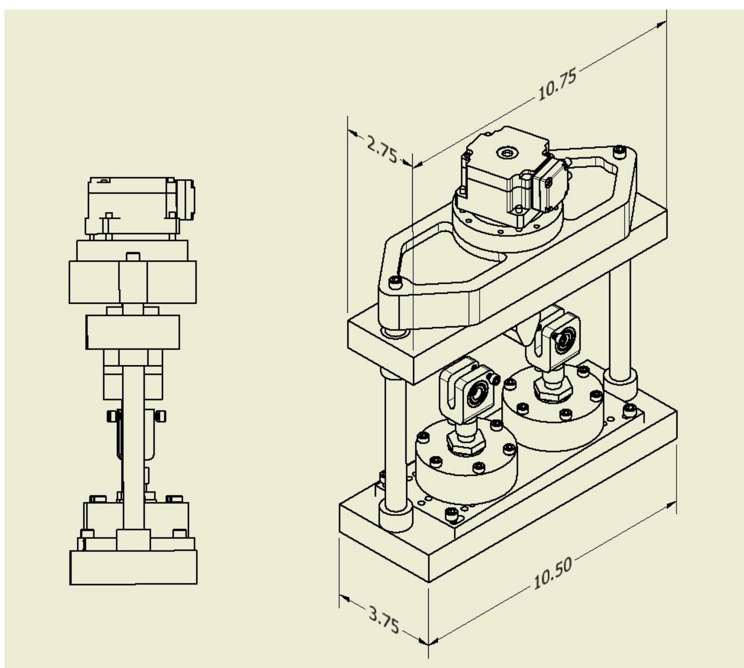
Appendix A:

Detailed Drawings with Dimensions:





Appendix B:

List of Materials:

Machined In-House:

- Bottom Plate
- Load Cell Plate
- Support Roller Saddle Fixture (x2)
- Alignment Fixture A (Load Cell Alignment)
- Alignment Fixture B (Support Roller Alignment)
- Loading Roller (x2)
- Loading Roller Plate (x3)
- 3 Point Bending Fixture
- Crosshead
- Top Plate
- Drive Screw
- Motor Mount
- Motor Hub

Acquired from McMaster-Carr:

- 2- 4 ½ Nylon-Tipped Screws
- 36 Bolts
- 2 Tapped Shafts
- 2 Threaded Load Cell Attachments
- 2 Collets
- 2 Clevis Pins
- 4 Ball Bearings
- 20 Alignment Pins
- 2 Brass Bushings

Appendix C:

Assembly/Alignment Instructions:

1. Place load cells on removable load plate.
2. Align load cells on plate with proper holes for desired distance.
    a. Inner holes for 96mm distance between bottom rollers,
    b. Middle holes for 112mm distance between bottom rollers,
    c. Outer holes for 128mm distance between bottom rollers.
3. Place alignment pins into load cell alignment fixture in correlating holes with the desired distance between bottom rollers.
4. Insert load cell alignment fixture into the load cell collets and tighten.
5. Fully tighten the screws attached to the load cells.
6. With fixture still attached to load cells, insert removable bottom plate into load frame.
7. Loosely screw removable plate into bottom plate of load frame.
8. Unscrew drive screw transfer plate from crosshead.
9. Drop crosshead down and insert alignment pins from top of the load cell alignment fixture into corresponding holes in the cross head.
10. Once fully aligned, tighten down screws between removable plate and bottom plate.
11. Loosen collets and raise crosshead
12. Reattach drive screw transfer plate to crosshead
13. Remove alignment fixture
14. Insert saddle rollers into collets on load cells.
15. Finger tighten collets
16. Loosen alignment screws on saddle fixtures.
17. Place specimen alignment fixture into saddle rollers.
18. Tighten alignment screws to barely touch specimen alignment fixture
19. Tighten collet with torque wrench.
20. Loosen alignment screws on same side ¼ turn.
21. Remove alignment fixture
22. Insert sample
23. Adjust sample until the load cells read the same value.
24. Tighten alignment screws ¼ turn.
25. Insert loading rollers using alignment pins for precision alignment and set to varying length for specified test and specimen length.
26. Screw in loading rollers.
27. Lower cross-head to top of beam.
28. Begin experiment.