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INVESTIGATING THE EFFECT OF LOADING ON A NORTH ATLANTIC RIGHT WHALE MANDIBLE

PROJECT TEAM:

Alexander Unrein
Robert Marsella
Matthew Packard

FOR:

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ABSTRACT

The endangered North Atlantic right whale population is threatened due to fatal collisions with ships. Before any major changes can be made regarding the safety of the whale population, more information is needed regarding the specifics of the collisions. An effort is underway to develop an accurate computer model of a right whale mandible so that computer simulations can be used to determine the effects the collisions have on the whale's jaw structure in the hope of preventing further collision related deaths.

To create an accurate computer model a method was developed to compare real-world measurements to results from computer simulations. The method consisted of establishing a set of physical constraints and load conditions that could be applied to an actual mandible then translated directly over to the computer model. This combination of tests allowed for a direct comparison of results between the two modes of testing.

A carefully calibrated series of load tests were applied to a right whale mandible, during which, strain and deflection measurements were made. The data collected from the physical testing is now available for use with the computer model using the Marc/MENTAT Finite Element Analysis (FEA) software package. Once the FEA model is calibrated to behave exactly like the physical mandible, it will be possible to execute a variety of collision scenarios without destroying any actual bones.

INTRODUCTION

BACKGROUND

The North Atlantic right whale is under a great deal of public and private concern due to their endangered status and shrinking numbers (see **Error! Reference source not found.**). According to the Woods Hole Oceanographic Institute (WHOI), 40% of the total mature right whale deaths are a result of collisions with marine vessels. While current regulations try to monitor and report collision incidents, they seldom work and approximately two fatal collisions occur each year. Before further regulations can be made, more information must be uncovered regarding the collisions. This information will be used to make better judgments toward regulations that should be passed.

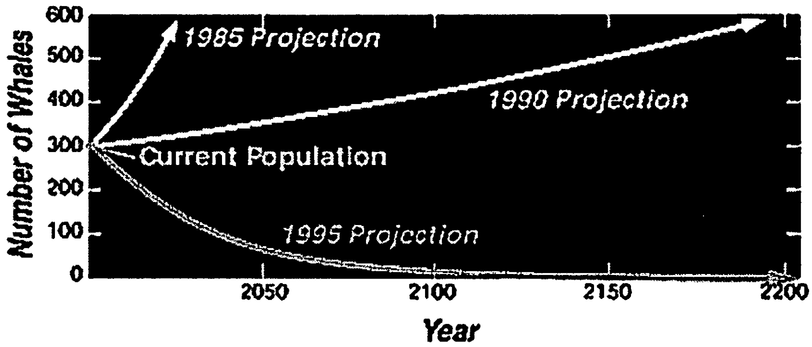

Figure 1 Whale Population Projections WHOI

Unlike most mammals, the NARW has two separate bones in their lower jaw. The two bones connect to each other at the "chin" of the whale with the help of tough fibrous tissue. The free ends of the mandible then attach to the skull via the mandibular joint, a ball and socket type joint located behind the whale's eye.

The mandibular joint is different than a regular ball and socket joint. In a right whale, the mandible rests up against a saucer like plate, held in place by a tough fibrous mesh. Even though the fibrous mesh is thick, it still allows enough resilience for the mouth to open and close. This fibrous material engulfs the ball end of the bone and travels down the bone until it reaches a spur-like protrusion (approximately two feet form the end of the bone, See Figure 2). Because of the tissue's role in the whale, its structural importance cannot be disregarded in the physical modeling.

The "chin" joint is also a unique attachment. When the whale feeds, its mouth opens while it swims, thus allowing its baleen to filter food from the water. The whale's feeding patterns have been compared to an ocean lawnmower, following the same back and forth sweeping action on the surface of the water while feeding. It has been observed that the jaw folds open during the feeding, turning its mouth into a giant funnel. The "chin" and mandibular joints allow this rotation which is estimated to be between 10 and 20 degrees.

FINITE ELEMENT ANALYSIS

Description of the model

A model of a single right whale mandible bone, created using a laser scan of the actual bone, was provided by WHOI. Judson DeCew at the University of New Hampshire Ocean Engineering refined the model, then imported into the FEA package Marc/MENTAT. The three dimensional solid model is comprised of approximately 18,000 quad elements with a scarce distribution of penta-elements. The ends of the model can be fixed in the x, y, and z axis with the option of moment constrains. All boundary conditions can be controlled as needed and multiple loading scenarios are possible, including fracture mechanics. **Error! Reference source not found.** shows the mandible model in the Pro Engineer (PRO/E) format.

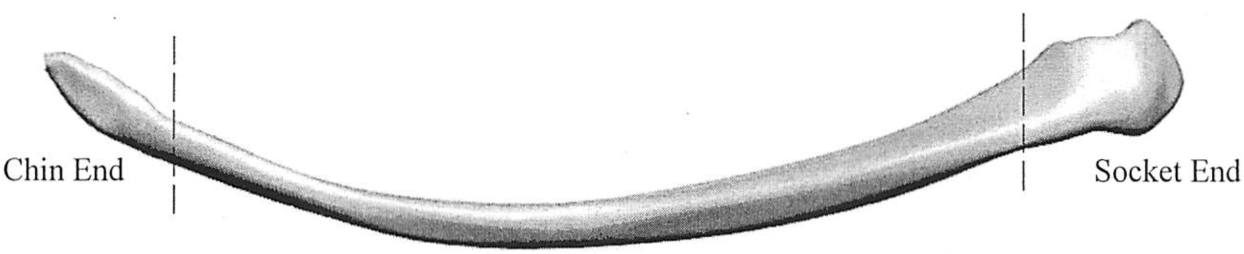

Figure 2 PRO/E Model of Mandible

Software Information

Data from the laser scan of the bone was inputted to the Rhino CAD package. An "*.igs*" type file was imported into PRO/E and Marc/MENTAT. Unfortunately, the transfer between RHINO and PRO/E did not transition smoothly and some information was lost. The poor transition inhibits the use of PRO/MECHANICA for the FEA Analysis which has slightly better visuals than Marc/MENTAT. The transfer of the "*.igs*" file from RHINO to Marc/MENTAT did however work, and no information was lost.

DESIGN PROCESS

DEVELOPING A TESTING METHOD

Design Criteria & Description of testing equipment

First assumptions suggested that the bone-testing fixture must constrain the bone similarly to the natural biological constraints experienced in the whale, including the compliancy associated with the joints. In addition, the testing fixture had to be non-invasive to the bone (i.e. no drilling holes), and the constraints used had to be transferable to the FEA model.

DESIGN ALTERNATIVES

The following two design alternatives were intended to be used with a large load-frame and hydraulic actuator located in Morse Hall on the University of New Hampshire campus.

Fixed Actuator

In this design the actuator is mounted on the underside of the load-frame and applies a downward force to the bone. The actuator remains fixed while the position of the bone is controlled to obtain all the needed angles of incidence. Strain gages and dial indicators are used for the acquisition of data during the static loading. The resulting design representing three superimposed positions for holding the bone is shown in **Error! Reference source not found.**. The actuator is represented by the cylinder.

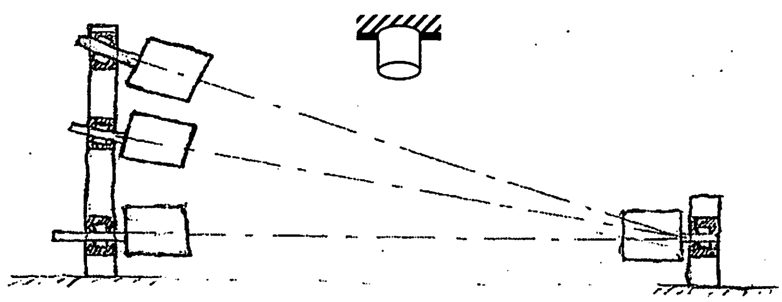

Figure 3 Fixed Actuator Design. Bone represented by dashed line

In **Error! Reference source not found.** each end of the bone (represented by the dashed lines) are located in a box that would contain compliant material used to emulate the natural joints of the whale. The boxes would be able rotate and change their elevation. The boxes are attached to steel towers which, in turn, are attached to a rigid steel strong-back. This strong-back would be able to transverse back and forth allowing for testing over the length of the bone.

A consensus was eventually made that this design is too complex for the scope of the project. The complexity of the design would make the theoretical modeling of the system difficult in addition to being difficult to manufacture. Various tests would require too many alterations to the setup, and the coordinate system would be constantly changing further complicating matters while allowing for increased error propagation.

Fixed Bone

Adhering to the prescribed testing criteria, it was decided that the bone could remain in place if the actuator could be moved. The ability to move the actuator would greatly reduce the complexity of the design while still providing the required testing conditions. After consulting with members of the Civil Engineering Department at the University of New Hampshire (UNH) the design was deemed feasible. This fixed bone design eliminates the reliance on the load frame, thus making it more versatile. The hydraulic actuator is mounted on a track system below the bone resulting in increased stability and system self-containment (see **Error! Reference source not found.**).

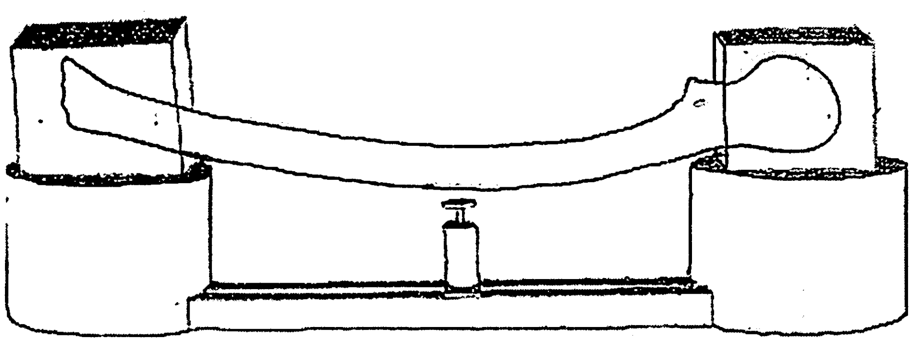

Figure 4 Fixed Bone Testing Fixture Design

Concrete pylons at either end would provide the desired rigidity for the joint fixtures to be attached to. Two steel box beams would connect the concrete structures and provide a platform for the actuator to sit on. The actuator could also be angled to obtain the needed angles of incidence, as well as translated from one end of the bone to the other, simulating various collision scenarios.

METHOD MODIFICATION

After careful consideration it was determined that the two design alternatives were too complex for the purpose of this project. The design alternatives would have too many constraining forces associated with them and would be difficult to accurately model in the computer analysis. Although a simpler setup would not simulate the bone constraints as existent in the whale, it would allow for a more controlled modeling of the bone.

FINAL DESIGN

Description

After reconsidering the design criteria the decision was made to hang the bone from a gantry crane and suspend weights from the bone (see **Error! Reference source not found.**). This design allows for the bone to be simply supported forgoing the complications associated with constraining moments. This design allows for greater ease when comparing the experimental tests on the bone to the computer simulations.

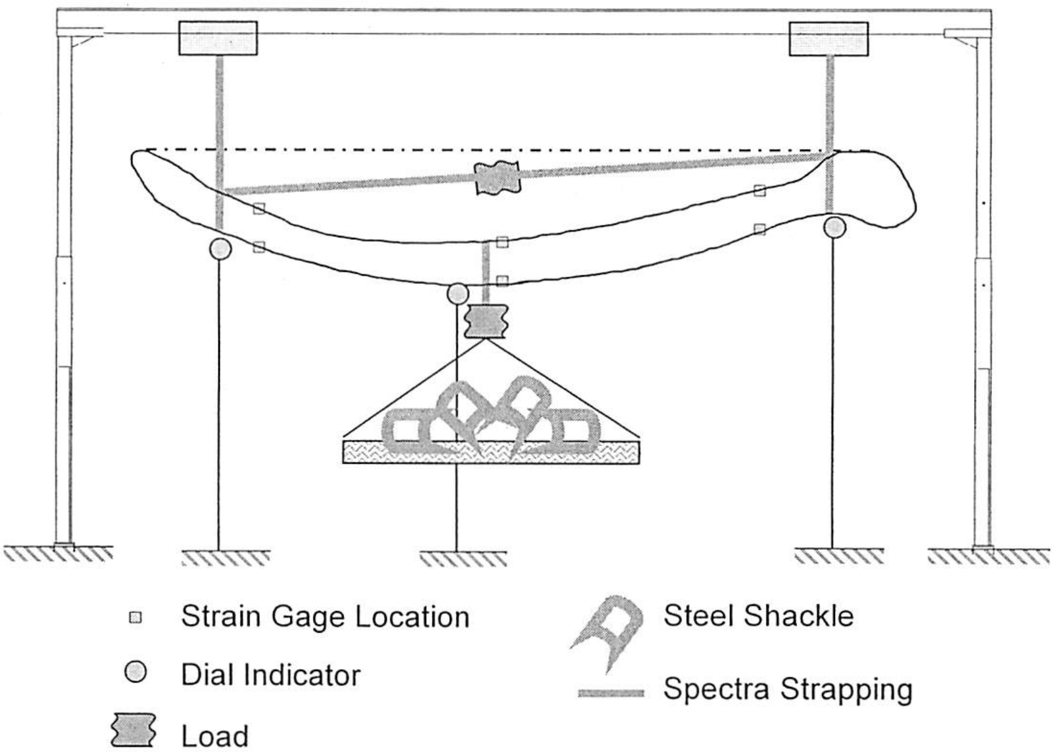

Figure 5 Final Testing Setup

The gantry crane was available from the Ocean Engineering Department and could be reconfigured to fit the project's requirements. The height could be set at 6, 8 or 10 ft, while the legs could be set at any location along the 19 ft I-Beam. In its testing position the crane was set at a height of 10 ft and a width of 16 ft.

Simply supporting the bone using non-rigid members allowed the bone to settle in an equilibrium position, thus eliminating moment constraints on the supports. The major concern with this configuration was the direction of the applied load. In this orientation the load no longer models a direct collision from the outside of the bone as would be the case in an actual collision. It was determined that the data collected using this orientation would still be useful in validating the computer model. Once the model is validated in this configuration it can then be used to run simulations with the load applied in the opposite direction.

PRELIMINARY TESTING

Minke Whale Testing

The experimental setup was tested on a small scale using a minke whale jawbone on loan from WHOI. This bone has similar geometry to that of the right whale mandible and provided the opportunity to develop and refine the data acquisition methods. For a complete set of testing procedures refer to the Final Testing section of this report.

Both strain and deformation data sets were recorded for two identical trials. Linear trends in the data showed elastic deformation taking place during the loading. This testing procedure and style of data acquisition was determined to be useful by Dr. Igor Tsukrov, who will be using the data to compare to numerical models developed later in research. A sample plot of the strain data taken from this test is shown in Figure 6, and deflection data is shown in Figure 7. Gages 1a, 2a, 3a, and 4a are Rosettes in the x direction (See Figure 8). Gages 5 and 6 are redundant gages oriented in the same direction as the "a" gages.

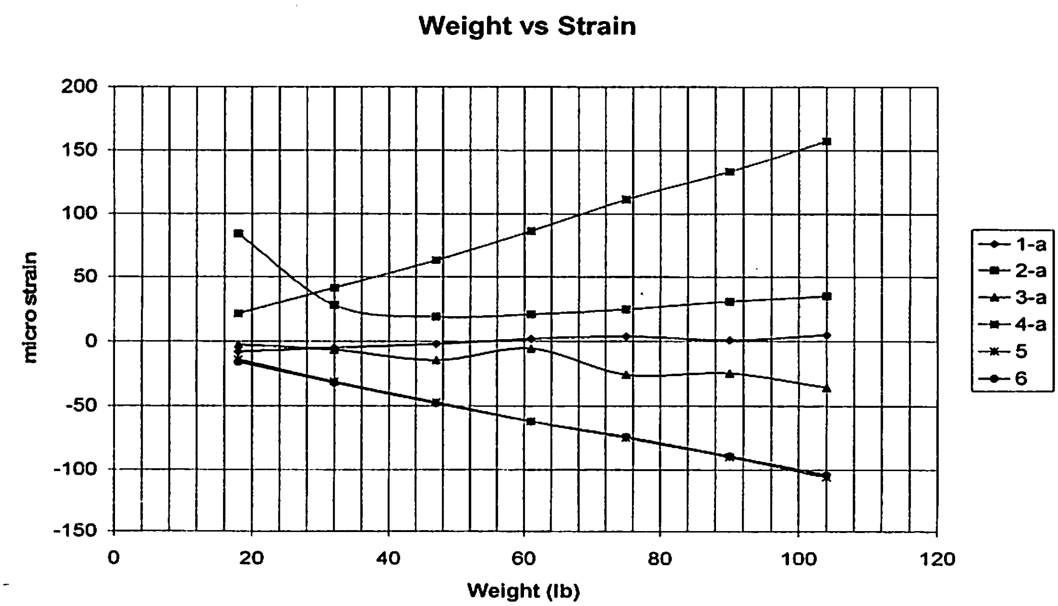

Figure 6 Minke Whale Strain Data

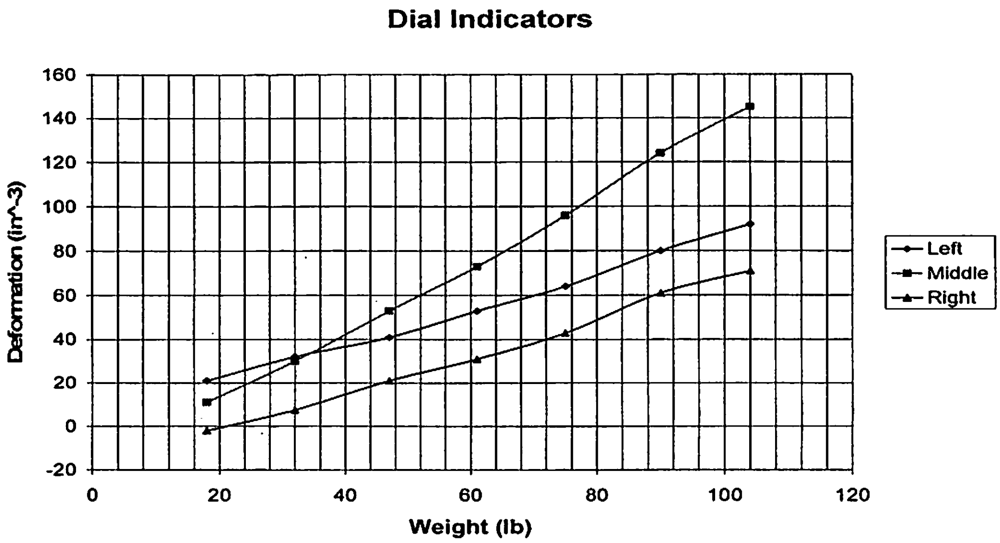

Figure 7 Minke Whale Deflection Data

During the minke tests, the strain gages were initially zeroed, then loads were applied in approximately 15 lb increments up to final a final load of 105 lbs. The load was then removed and the zeros of the gages recorded. Due to differences in the zeros, it was decided that the zeros would have to be read both before and after each load increment for the right whale testing, thus allowing for more accurate strain measurements.

FINAL TESTING

On April 6, 2005, a North Atlantic Right Whale mandible was removed from the freezer at WHOI and transported to the Chase Ocean Engineering building at UNH. Throughout the following week all tests were preformed and data were recorded.

Preparation of Bone

Thawing

It was required to thaw the bone for a minimum of two days in a temperature over 50-degrees Fahrenheit, before any testing or gage mounting could begin. If strain gages are applied to the bone before fully thawed, the bond could be compromised and result in a inaccurate measurements.

Orientation and Coordinate System

Orientation

It was determined to model the mandible as a simply supported beam allowing for all the forces to lie in a single plane. This was accomplished by hanging the bone from a beam and while hanging weights from the bone. In this orientation the concave side of the bone will be referred to as the "Top" and the convex side as the "Bottom".

Coordinate System

A precise coordinate system would be needed to relate the strains and deflections of the Right Whale Mandible to the finite element model. Since the bone was hung from a structure, gravity decided the first major axis for the coordinate system. Two distinctive points were then chosen on the bone ends. Connecting these points with a piece of string and a level created a second axis. The third axis was set normal to the plane made by the other two mutually perpendicular axes. The layout and coordinates of the straps and strain gages on the mandible can be viewed below. All comments about the strain gage placements are in reference to the figure drawing.

Coordinate System – The x axis starts at the top left most point of the bone and runs across horizontally to a point on the other end of the bone. The y axis is in the direction of gravity. The third degree of freedom necessary to transfer the location during live testing to the numerical model is the surface of the bone (See Figure 8). Coordinates for all strain gages and strap locations can be found in Table 1.

Supports – The bone is supported by two one-inch spectra strapps on the left at site A, and right at site C. (See Figure 9)

Force – Weights were hung by two one-inch spectra strapping at site B. (See Figure 9)

Strain Gages – One strain gage rosette with gages at 0, 45, and 90 degree and one axial gage running in the x direction was placed at each strain gage site (1, 2, 3, 4, 5, 6). Sites 1, 3, and 5 are considered to be the "top" of the bone, while sites 2, 4, and 6 are considered to be the "bottom" of the bone. (See Figure 9)

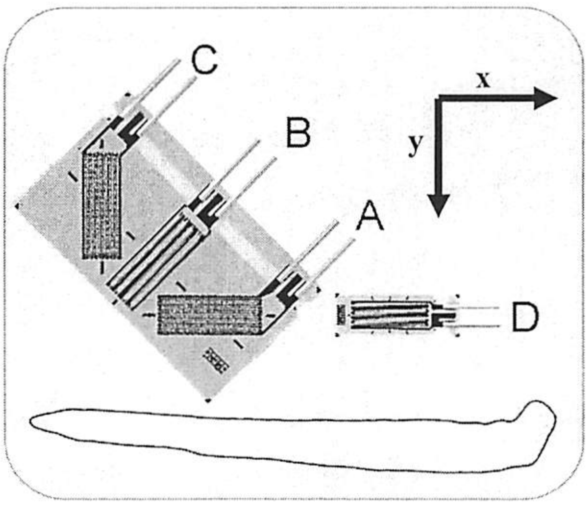

Figure 8 Strain Gage Layout and Coordinate System

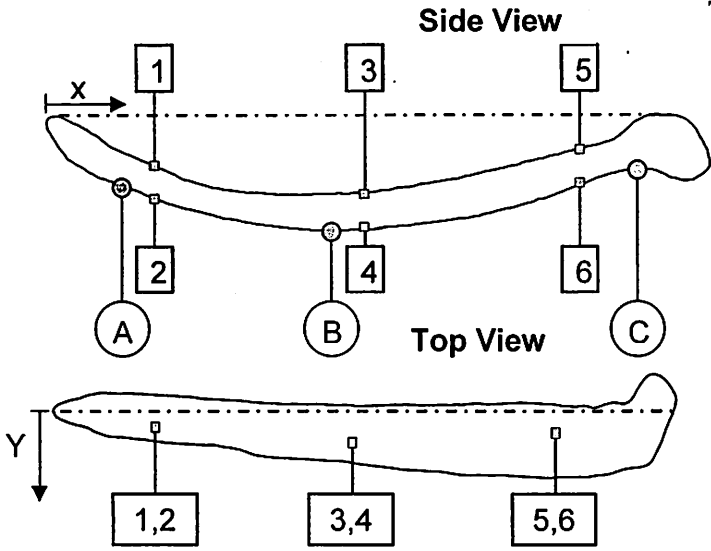

Figure 9 Strain Gage Placement on Bone

Table 1 Strain Gage X,Y Coordinates

Site	X Axis (in)	Y Axis (in)
1	35.75	4.25
2	35.75	4.25
3	77.50	6.50
4	77.50	6.50
5	108.75	4.50
6	108.75	4.50
A	21.50	5.0
B	70.00	6.0
C	139.5	4.0

Once the setup of the coordinate system was complete, measurements to each of the strain gages, dial indicators, support straps and load were recorded (See Table 1). Extensive pictures were taken of each of the end joints where the points lay for comparison with the computer model. Measurements were taken from the points to the sides of bone on their respective ends. From these pictures and measurements, coordinate comparisons can be made between the finite element model and the physical testing.

Strain Gage Application

Gage placement

Three crucial sections of the bone were considered for strain gage readings. Strain gages were placed near the middle and approximately one meter from each end of the bone. At each section a Rosette was placed on the top and bottom of the bone with a redundant axial strain gage in the x axis (See Figure 8). These axial strain gages were used to validate each rosette gage reading.

Gage application

The procedure for application of the strain gage came from a manual provided by Vishay Measurements. A detailed and comprehensive procedure can be found in Appendix C.

Wire Selection and Setup

A nine strand wire was used for the gage connections. Each gage needs three strands; a positive, a negative, and a ground. One length of nine strand wire satisfied one rosette or three axial gages. For each section there were three lengths of wire (2 rosettes and 1 axial gage). With three sections, this resulted in a total of nine lengths of wire. Each length of wire was cut eleven feet long, for a total of ninety-nine feet of wire.

A terminal was applied close to each gage for ease of soldering. The terminal served as a breakaway safety device. If for any reason the wires were ripped away from bone, the terminal would rip off instead of the strain gage. The bottom gages were connected while the bone was still on the ground. After all soldering was complete each strain gage and terminal was layered with a coat of wax. The wax was used for protection of the strain gage, terminal, and wires from any unwanted contact.

Switch and Balance/Strain Indicators

The Mechanical Engineering Department at the University of New Hampshire provided three P3500 Strain Indicators and three Switch and Balance units. Each Switch and Balance unit provided ten channels for a total of thirty channels. For the test a total of twenty four channels were used. A detailed informational sheet for both the strain indicator and switch & balance units can be found in Appendix B as well.

Dial Indicator Application

Testing Platform

Rigid metallic testing platforms were constructed to position the dial indicators close to the bone. The dial indicators were attached to the steel posts with magnets and c-clamps for added stability (See Figure 10). The base of each beam was bolted to a quarter inch steel plate two feet long by two feet wide. Three supports were welded to the bottom of the plate with the purpose of eliminating any possibilities of rocking.

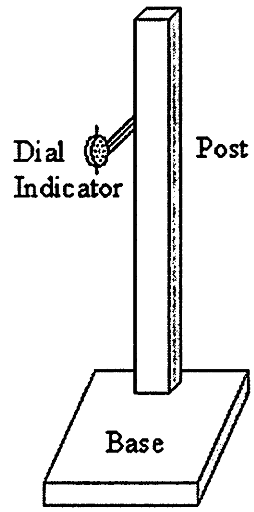

Figure 10 Dial Indicator Platform

Indicator Placement

The dial indicators were placed at the critical points needed to obtain total deflection of the bone. The left and right vertical dial indicators were attached at the very bottom of the bone directly under the straps that suspended the bone in the air. The middle indicator proved to be a bit more challenging. The indicator needed to be placed in the middle of the bone at the place where the load was being applied. However the load itself prevented the testing platform and dial indicator from getting close enough to the bone for testing.

Testing

Hanging the Bone

The mandible was hung from a gantry crane acquired from the Ocean Engineering facilities at the University of New Hampshire. Measurements of the crane were taken and calculations of worse case scenario were computed to determine if the crane would suffice for the experiment. It was determined that even with a safety factor of two the crane would be able to support the weight without any complications. For complete dimensions and calculations see Appendix D.

A one ton trolley was attached to each end of the I-beam. These would act as the point where the straps would connect to the crane allowing for movement back and forth along the beam. Before testing each trolley was kept in place by a set of clamps to prevent the bone from slipping out of the straps.

Spectra strapping was used to hang the bone instead of rope. Spectra has lower creep and elongation, and maintains the desired amount of strength without becoming extremely bulky. To hang the bone a length of spectra was tied in a loop as a saddle that the bone sat in while a carabineer connected the loop together over the top of the bone. Chain hoists were used to connect the trolleys to the strapping around the bone allowing for precision leveling and less of an effort to raise the bone from its resting position on the ground.

Two load cells were used to obtain the weight of the bone before testing. A Dynamometer, provided by Woods Hole was placed at one end between the chain hoists and the spectra around the bone. At the other end a 5000 lb load cell was applied in the same manner. The chain hoists were then raised and the weight recorded. Once the data were acquired the load cells were switched and the process was repeated. The bone weighed 487 lbs. After testing the process was repeated to determine how much weight the bone had lost through oil loss and other factors. At the end the bone weighed 496 lbs, surprisingly higher than the original weight. This was due to the additional straps attached to the bone during the second weighing.

Weight Application

Weights were applied to a point near the middle of the bone. The original design was to use a blue plastic water container, fill it with water and simply hang this container from the bone. This idea was later dismissed when it was realized there was insufficient room between the bottom of the bone and floor to hang the container. The alternative method was to hang a pallet and apply increments of 18 lb shackles. The downside to this approached is that the increments no longer increased by exactly 100 lbs each time, but by keeping careful records of the actual weight with the shackles no problems were encountered with weight increment.

In between the pallet and the bone was connected the previously mentioned 5000 lb load cell. This load cell was crucial in determining the exact amount of weight applied to the bone.

Testing

The first tests of the North Atlantic Right Whale mandible occurred on the morning of April 10, 2005. The average temperature during testing was 70 degrees Fahrenheit. Strain gages were zeroed before the bone was suspended. This enabled the strains due to the bones weight to be assessed. The bone was then hung from the structure, and the strain gages were again read and recorded.

The strain measurements were then read and recorded in increments of approximately 100 lbs. After every 100 lb increment was applied, the weight was taken off and the zeroes read again. This produced an average zero offset that was later used for the correction of strain values. The process continued until a desired weight of 1000 lbs was achieved. The second and third tests were simplified slightly. Weights were increments by 200 lb for every reading up to a final weight of one thousand pounds.

After all strain gages were tested three times, weights were applied one last time to measure the deflection using the dial indicators. Before the test all indicators were zeroed and recorded. Weights were applied in approximately 200 lb increments and dial indicator measurements were read and recorded. However, unlike the strain gages, the dial indicators did not need to have the zero read after every load was applied. At 1000 lb the testing was finished and weights were removed. Pictures of testing apparatus and data acquisition set up can be found in Appendix F.

Storage

Clean Up and Removal

After acquiring the bone for testing it was wrapped in cellophane to reduce the odors emitted from the bone and to contain the oil within the bone. The strain gages remained attached to the bone so they could be incorporated into the CAT scans with hopes of aiding comparison of the positioning of strain gages in experimental testing to computer model testing. The wires from the strain indicators to the gages were cut, leaving about 2 inches of wire left of the strain gage. The dial indicators were then removed and cleaned. The areas of the bone that held the strain gages were again wrapped in cellophane and the bone was removed form its straps. For transportation purposes the entire bone was wrapped in industrial plastic.

Cooling Container

The bone needed to be stored in a cool place on completion of testing before it was returned to Woods Hole. Since no cooling storage was readily available a suitable alternative needed to be constructed. A 16'x 4'x 4' wooden box was built to house the bone for its remaining duration at UNH. The box was insulated with one inch R-6.5 foam for cooling. Once the bone was stored inside ice was placed over it and the top sealed shut. Upon departure the crate had maintained a temperature of 39 degrees Fahrenheit. It is safe to assume this was the temperature it was stored at. Later on that day it was returned to Woods Hole and stored in a freezer.

PRESENTATION AND DISCUSSION OF RESULTS

A full collection of data acquired from the testing can be found in Appendix A. Below in Figure 11 strain readings from gages in the x direction can be found for one site. Graphs and data from all other sites and strain positions can also be found in Appendix A. All d-labeled data on the graphs are redundant x axis gages placed at local sites to confirm proper strain readings from rosettes. Below in Figure 8 strain gages Test1_1a, Test2_1a, and Test3_1a are the gages on the Rosette in x direction. Gages Test1-1d, Test2-1d, and Test3-1d are the redundant gages running in the x direction.

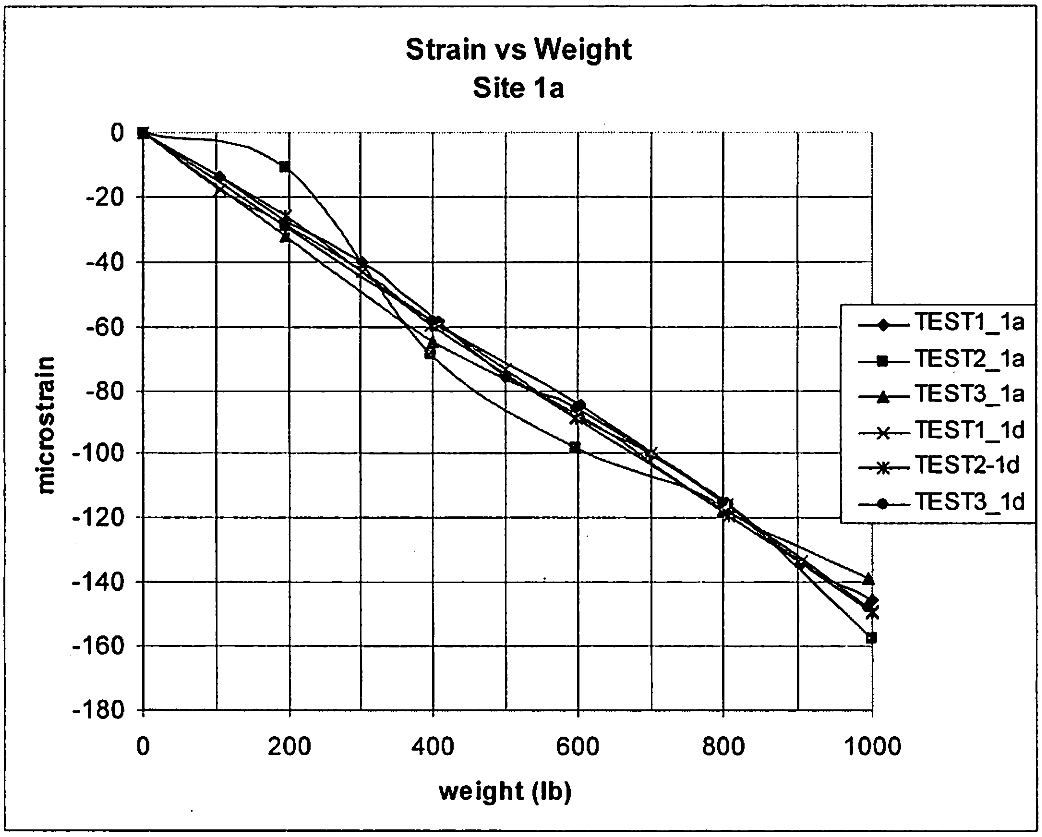

Figure 11 Example Right Whale Strain Data

The data from the graph above is from test 1, 2, and 3 at site 1, (see Figure 9). This graph show that the redundant gages fall within a very small error percentage from the rosette x direction gages. Similar results can be found for all other sites (see Figure 9). This implies that the application and reading of all strain gages were done with equivalent precision.

Maintaining the bone in a hanging position required a horizontal strap to keep the supports from sliding off the bone due to irregular geometry at the ends. This clearly produces a reaction force at the support locations. A load cell was attached to this horizontal strap and loads produced through testing can be seen below in Figure 12.

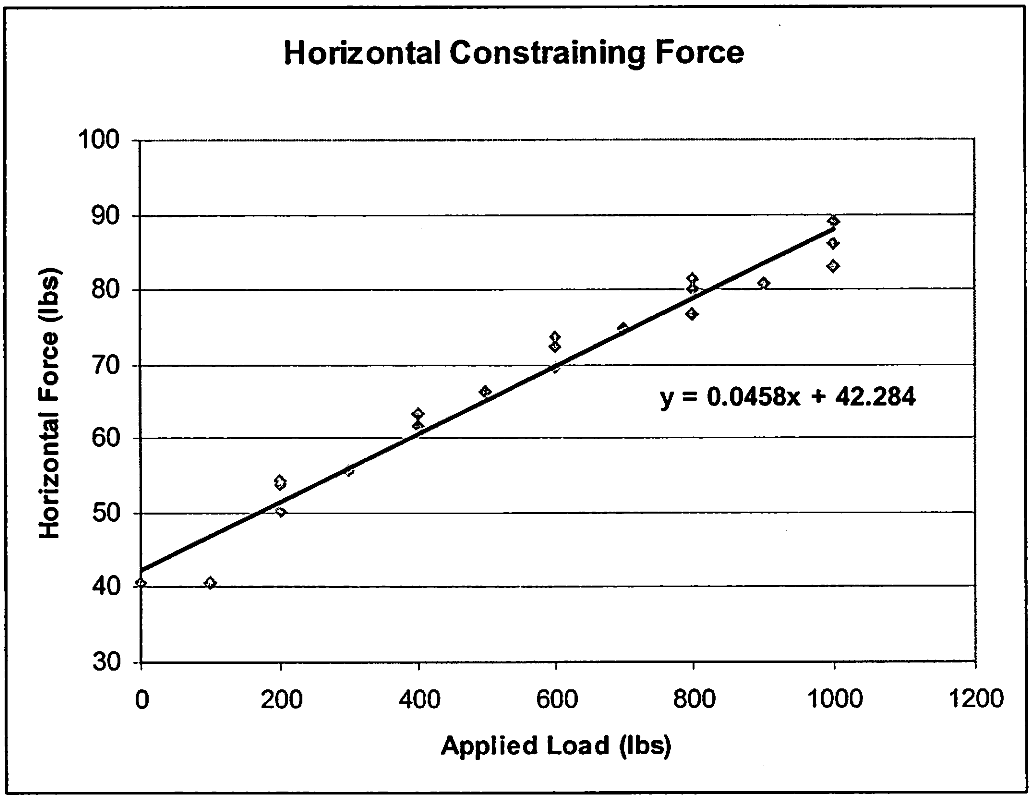

Figure 12 Horizontal Load Data

From the graph above a 1000 lbf load application to the bone in the y direction results in a maximum resulting force of 88 lbf in the x direction. The forces shown above are slightly larger than what was expected but are still believed to have little to no effect on the strain readings because the increase was less than 50 lbs. However, these forces can be factored into the final numerical model if needed.

Displacement of the end supports and center of the bone were also monitored with the use of dial indicators. The irregular geometry of the bone caused slight error in the displacement readings but can still be approximated with a linear fit. A graph of these results can be viewed below in Figure 133.

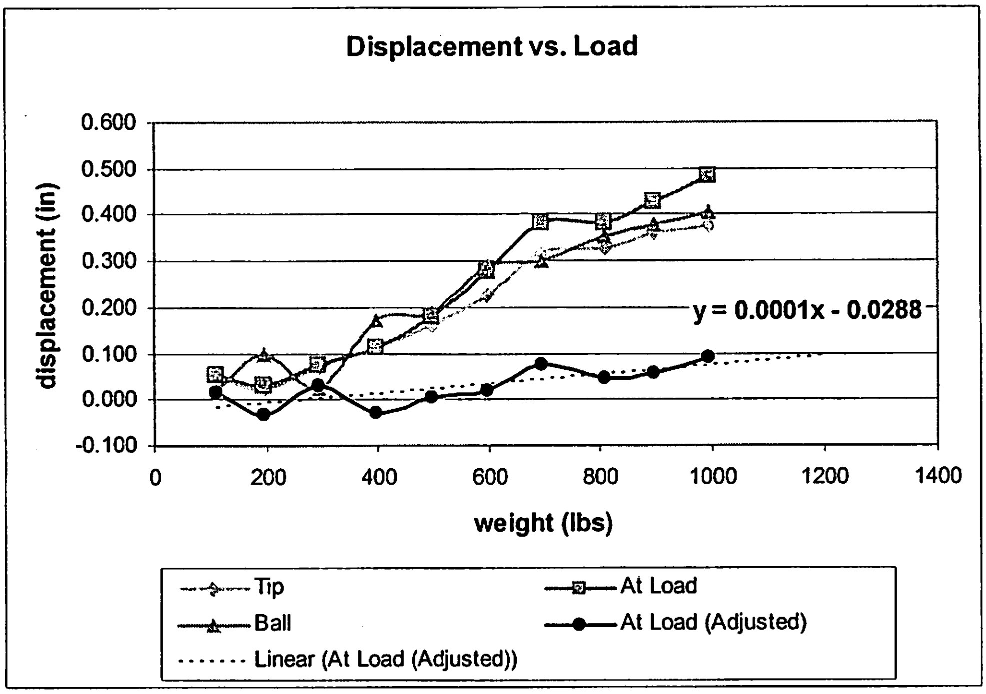

Figure 13 Right Whale Displacement Data

The two end support readings were averaged to obtain the displacement of the end supports from the stretching of the spectra straps. This was subtracted from the displacement of the middle of the bone to obtain the actual displacement of the bone material which is represented as the At Load (Adjusted) data plot above in Figure 13. The linear approximation of the corrected displacement yields

$$y = 0.0001x - 0.0288. \qquad \textbf{Equation 1}$$

At a maximum weight application of approximately 1000 lbf the displacement of the bone is .0712 inches. This is a displacement less than one tenth of an inch and falls well within the bounds of our desired safety factor of three.

Post Testing Improvements

Improvements

Dial indicator testing presented the most problems for any part of the entire project. As the bone was hung from the straps it would settle into position. At this point the dial indicators were put into position and zeroed. Once a load was applied to the bone it rotated due to the irregular geometry of the surface. The rotation resulted in an induced vertical displacement which effected the vertical measurements made using the dial indicators.

The strain gages worked very well for the most part. Many improvements were made from the testing of the minke whale mandible. However, a few gages gave questionable data. By completely allowing the bone to thaw the interaction between the gage and the bone would not be compromised. Larger strain gages would also result in better data. This is due to the fact that there would be more averaging of strain in a localized area which tends to be better for porous material. After preparation of the bone surface, sections where cracks and imperfections were clearly visible. The gages were placed as carefully as possible to avoid these imperfections.

Conclusion

The data collected from this project will hopefully improve the overall understanding of collisions between ships and North Atlantic right whales. The improved understanding could pave the way for reforms on shipping regulations, in turn lessening the detrimental effects of the collisions on the North Atlantic right whale species.

Three main prospects arise from all the collected data, research, and testing done throughout this project. The first is the establishment of a protocol for testing the mechanical behavior of large whale bones.

Secondly, the raw data acquired from the testing will be used to confirm and compare the numerical currently being developed by Professor Igor Tsukrov at the University of New Hampshire along with project engineer Judson DeCew. The data were presented in graphical and tabular form in the Appendix A and can now be used to compare results from numerical model simulations.

Raw data from these tests can also be used to develop models of stress-strain relationships. Future small scale testing of the bone done through CAT scans will assist in the acquisition of material properties such as Young's modulus and Poisson's ratio which are necessary to complete the computer model. These properties have been previously determined using Right Whale vertebrae as a function of the mineral content, bone density, and Young's modulus (Currey).

Aside from comparison of the simply supported structure with the computer model and small scale compression and tension testing, it would be possible for the end supports to become more complicated and more controlled. This would provide new sets of data to compare with other scenarios tested with the computer model. There are many possibilities for advancement with this project with the main goal of some day determining the fracture mechanics of these whale bones and possibly preventing more mortalities of this endangered species.

BUDGET

A budget of $3,000 was allotted to this project. The following is a complete list of project expenses totaling $2,385.71.

Materials

Table 2 Strain Gage Budget

Item	Vendor	Quantity	Cost/Unit	Total Cost
3140 RTV Silicone Rubber (3-oz)	Vishay	1	$28.40	$28.40
CEG-100D Terminals (15/pkg)	Vishay	2	$10.70	$21.40
Gauze	Brooks Pharmacy	4	$2.99	$11.96
GC-6 Isopropyl Alcohol	Vishay	2	$6.20	$12.40
L2A-06-250LR-350 Strain Gages (5/pk)	Vishay	15	$18.15	$272.25
L2A-06-250LW-350 Strain Gages (5/pk)	Vishay	20	$4.73	$94.50
M-Bond 200 Kit	Vishay	2	$34.20	$68.40
M-Coat W-1 Kit	Vishay	1	$23.00	$23.00
Primary Wire	Houghton Hardware	3	$3.19	$9.57
Sanding Kit	Home Depot	1	$4.97	$4.97
Tweezers	Brooks Pharmacy	2	$1.49	$2.98
Wire (9 conductors)	Digi-Key	1	$57.83	$57.83
Strain Gage Application Sub-total				**$607.66**

Table 3 Cooling/Storage Budget

Item	Vendor	Quantity	Cost/Unit	Total Cost
1" Insulation (4'x8')	Home Depot	9	$14.57	$131.13
2 1/2" screws	Home Depot	1	$19.22	$19.22
2x4-10' Stud	Home Depot	4	$4.15	$16.60
2x4-96" Stud	Home Depot	20	$2.89	$57.80
3" Screws	Houghton Hardware	2	$4.99	$9.98
Carpenter Pencil	Home Depot	2	$0.39	$0.78
Composite Board (4'x8')	Home Depot	9	$15.25	$137.25
Great Stuff	Houghton Hardware	2	$4.49	$8.98
Screw Bits	Home Depot	1	$4.97	$4.97
Cooling/Storage Box Sub-total				**$386.71**

Table 4 Miscellaneous Materials Budget

Item	Vendor	Quantity	Cost/Unit	Total Cost
1 1/2" - 1/2" Bolts	Houghton Hardware	1	$5.49	$5.49
1" Tubular Spectra Webbing (80 ft)	Imlay Canyon Gear	1	$38.00	$38.00
1/2" Nuts	Houghton Hardware	6	$0.60	$3.60
1/2" Washers	Houghton Hardware	1	$2.89	$2.89
AAA Batteries	Home Depot	1	$4.87	$4.87
Black Permanent Marker	Brooks Pharmacy	1	$1.49	$1.49
Duct Tape	Home Depot	1	$3.97	$3.97
Ear Plugs	Houghton Hardware	1	$7.99	$7.99
Electrical Strip	Houghton Hardware	1	$4.99	$4.99
Electrical Tape	Home Depot	1	$2.49	$2.49
Glad Wrap	Durham Market Place	2	$2.19	$4.38
Leather Work Gloves	Houghton Hardware	1	$4.99	$4.99
Lighter	Brooks Pharmacy	1	$0.89	$0.89
Nitrile Gloves	Home Depot	2	$4.96	$9.92
Nylon Rope	Home Depot	1	$6.69	$6.69
Nylon Twine	Houghton Hardware	1	$5.49	$5.49
Plaster of Paris	Houghton Hardware	1	$3.49	$3.49
Plastic Sheeting	Home Depot	2	$15.37	$30.74
Push Pins	Brooks Pharmacy	1	$1.99	$1.99
Red Permanent Marker	Brooks Pharmacy	1	$1.49	$1.49
Shop Towels	Home Depot	1	$1.92	$1.92
Small Brushes	Home Depot	1	$1.66	$1.66
Trash Bags	Home Depot	1	$10.47	$10.47
Velcro Hanging Straps	Home Depot	1	$7.99	$7.99
Wipes	Home Depot	2	$1.66	$3.32
	Miscellaneous Materials Sub-total			**$171.21**

Table 5 Instrumetns/Equipment

Item	Vendor	Quantity	Cost/Unit	Total Cost
3" Line Aluminum Line Level	Houghton Hardware	1	$2.99	$2.99
Dial Indicator/Magnetic-Base Set	McMaster-Carr	5	$29.71	$148.55
Lightweight Cartridge Respirator	McMaster-Carr	1	$14.89	$14.89
Plumbbob	Houghton Hardware	1	$4.99	$4.99
Utility knife	Houghton Hardware	1	$5.99	$5.99
Versatile-Mount Push Trolley	McMaster-Carr	2	$130.55	$261.10
	Instruments/Equipment Sub-total			**$438.51**

Table 6 Transportation Budget

Item	Vendor	Quantity	Cost/Unit	Total Cost
Mileage	N/A	160	$0.38	$60.00
Diesel	Exxon Mobil Corp.	15	$2.40	$35.99
Rental Truck	Ryder	1	$600.00	$600.00
Tolls		1	$2.00	$2.00
Train Tickets (Boston-Durham)	Amtrak	2	$13.00	$26.00
	Transportation Sub-total			**$723.99**

Table 7 Miscellaneous Items Budget

Item	Vendor	Quantity	Cost/Unit	Total Cost
Color Copies	MUB Copy Center	1	$6.80	$6.80
Shipping	McMaster-Carr	1	$21.50	$21.50
Shipping	Vishay	1	$29.33	$29.33
			Sub-total	**$57.63**

Table 8 Expense Summary

Expense Summary	Cost
Materials	
Strain Gage Application	$607.66
Cooling/Storage Box	$386.71
Miscellaneous	$171.21
Instruments/Equipment	$438.51
Transportation	$723.99
Miscellaneous	$57.63
Total Cost of Project	**$2,385.71**

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Woods Hole Oceanographic Institution: Ocean Life Institute
http://www.whoi.edu/institutes/oli/index.htm

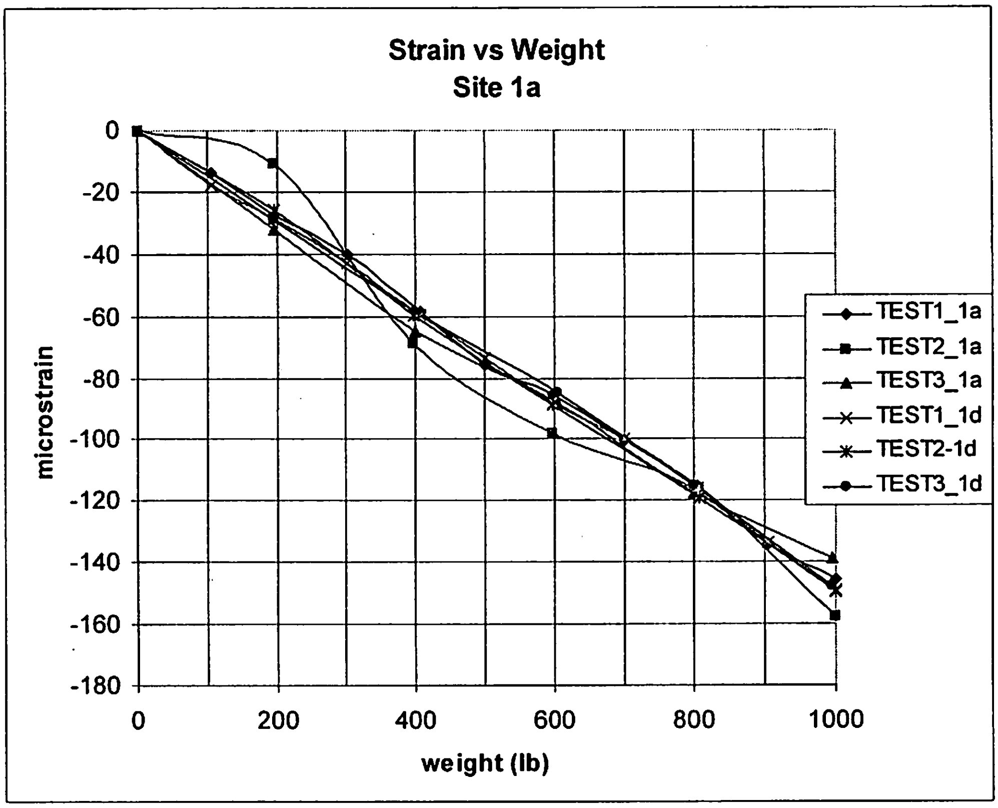
Contacts and Advisors

(1) Prof. Kenneth C. Baldwin; Ocean Engineering, University of New Hampshire; 862-1898; kcb@unh.edu
(2) Prof. David L. Gress; Civil Engineering, University of New Hampshire; 862-1410; david.gress@unh.edu
(3) Prof. Raymond A. Cook; Civil Engineering, University of New Hampshire; 862-1411; ray.cook@unh.edu
(4) Prof. Charles H. Goodspeed; Civil Engineering, University of New Hampshire; 862-1443; chgi@christa.unh.edu
(5) Judson C. Decew; Ocean Engineering, University of New Hampshire; 862-4256; jcdc@unh.edu
(6) Prof. Igor I. Tsukrov; Mechanical Engineering, University of New Hampshire; 862-2086; igor.tsukrov@unh.edu
(7) Regina Campbell-Malone; Graduate Student, Wood Hole Oceanographic regina@whoi.edu
(8) Michael Moore; Wood Hole Oceanographic Institute mmoore@whoi.edu

Appendix A: Numerical Results

Placement of strain gage on bone can be found in Figure 9

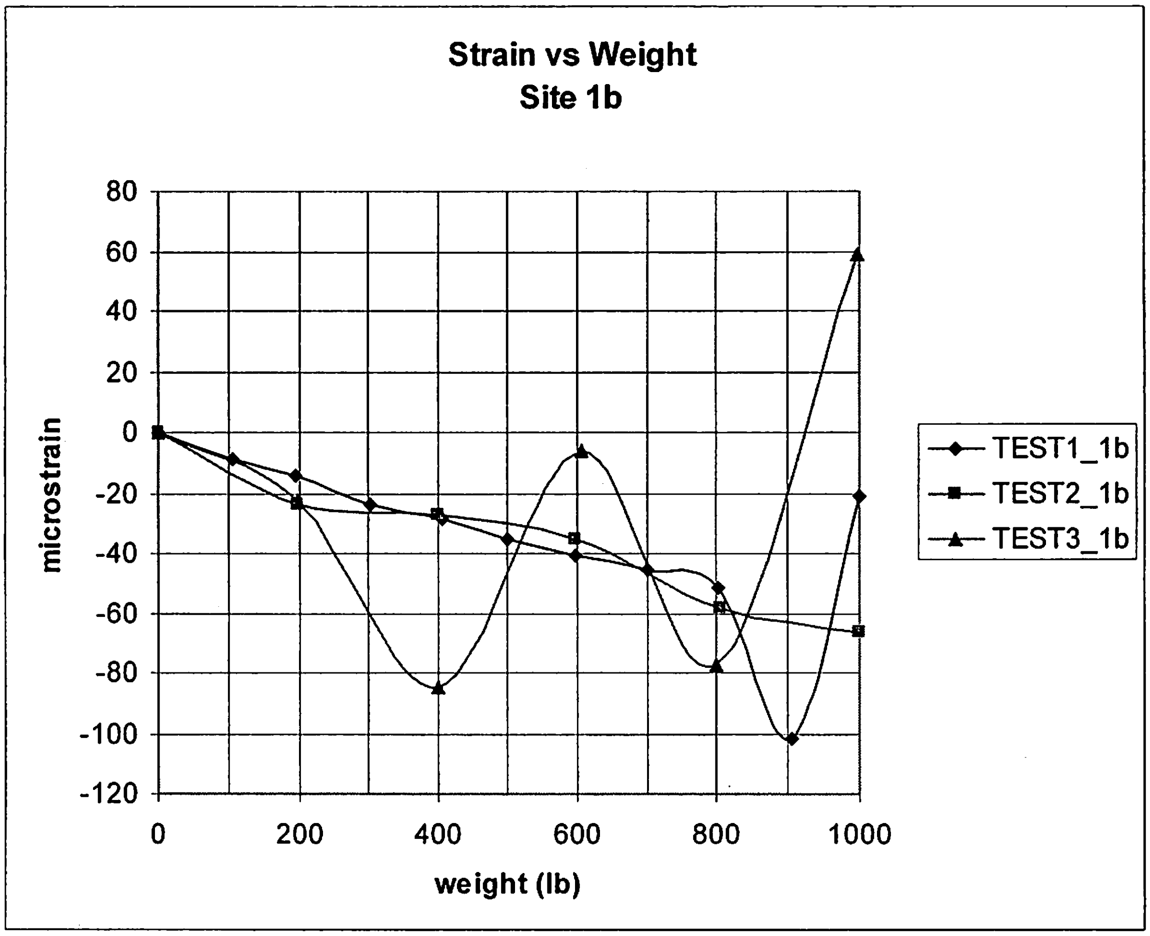
1a



weight	TEST1_1 a	TEST2_1 a	TEST3_1 a	TEST1_1 d	TEST2_1 d	TEST3_1 d	AVERAGE
0	0	0	0	0	0	0	**0.00**
100	-13.5			-17.5			**-15.50**
200	-27.5	-11	-32	-28.5	-26	-29	**-25.67**
300	-40			0.43			**-19.79**
400	-58.5	-69	-64.5	-59.5	-59.5	-58.5	**-61.58**
500	-75.5			-73.5			**-74.50**
600	-85.5	-98	-88.5	-88	-89	-85	**-89.00**
700	-100.5			-100			**-100.25**
800	-115	-117.5	-117.5	-116	-119.5	-115	**-116.75**
900	-134			-133.5			**-133.75**
1000	-145.5	-157.5	-139	-149	-149.5	-148	**-148.08**

NOTE:
weight within 1% error

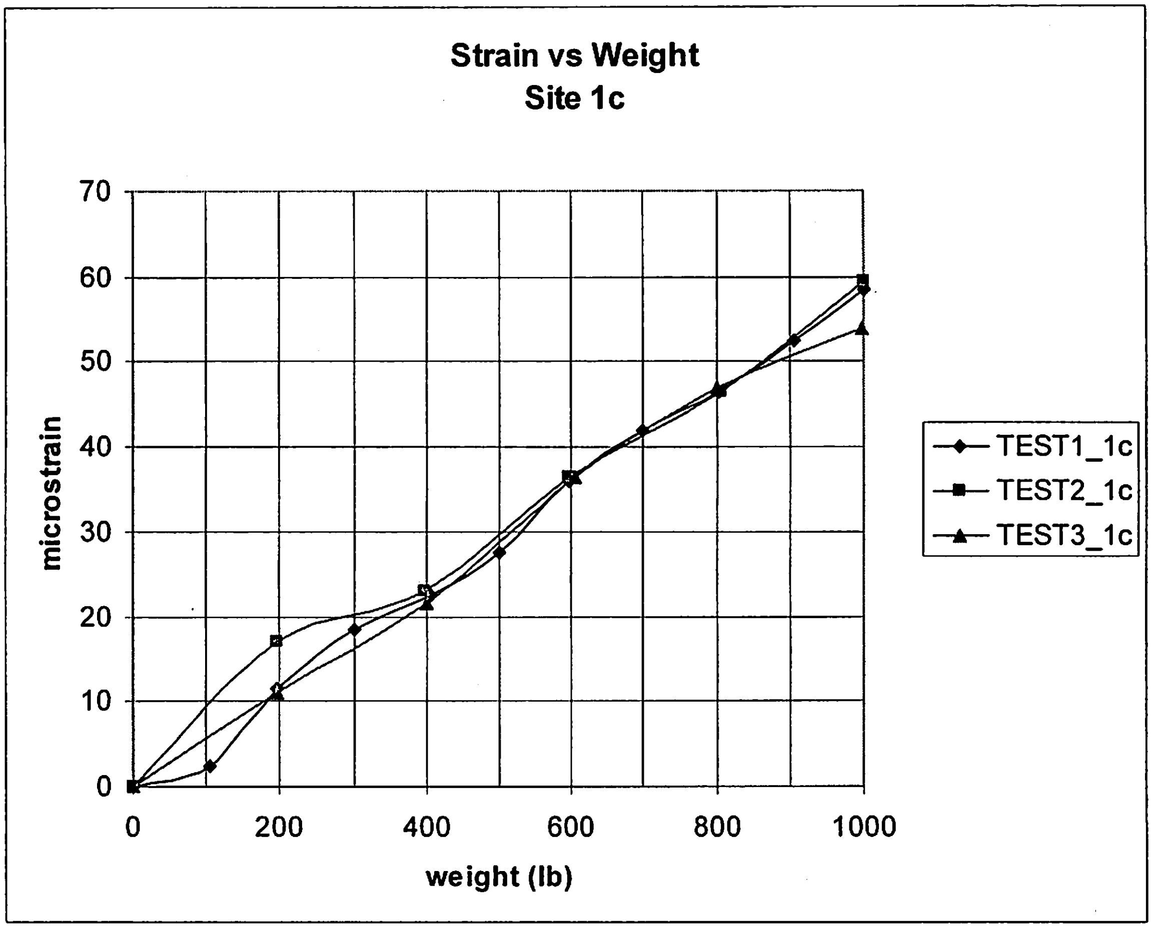
1b



weight	TEST1_1b	TEST2_1b	TEST3_1b	AVERAGE
0	0	0	0	**0.00**
100	-9			**-9.00**
200	-14.5	-24	-22.5	**-20.33**
300	-23.5			**-23.50**
400	-28.5	-27	-85	**-46.83**
500	-35.5			**-35.50**
600	-40.5	-35	-6	**-27.17**
700	-45.5			**-45.50**
800	-51.5	-58	-77.5	**-62.33**
900	-102			**-102.00**
1000	-21	-66.5	59	**-9.50**

NOTE:
weight within 1% error

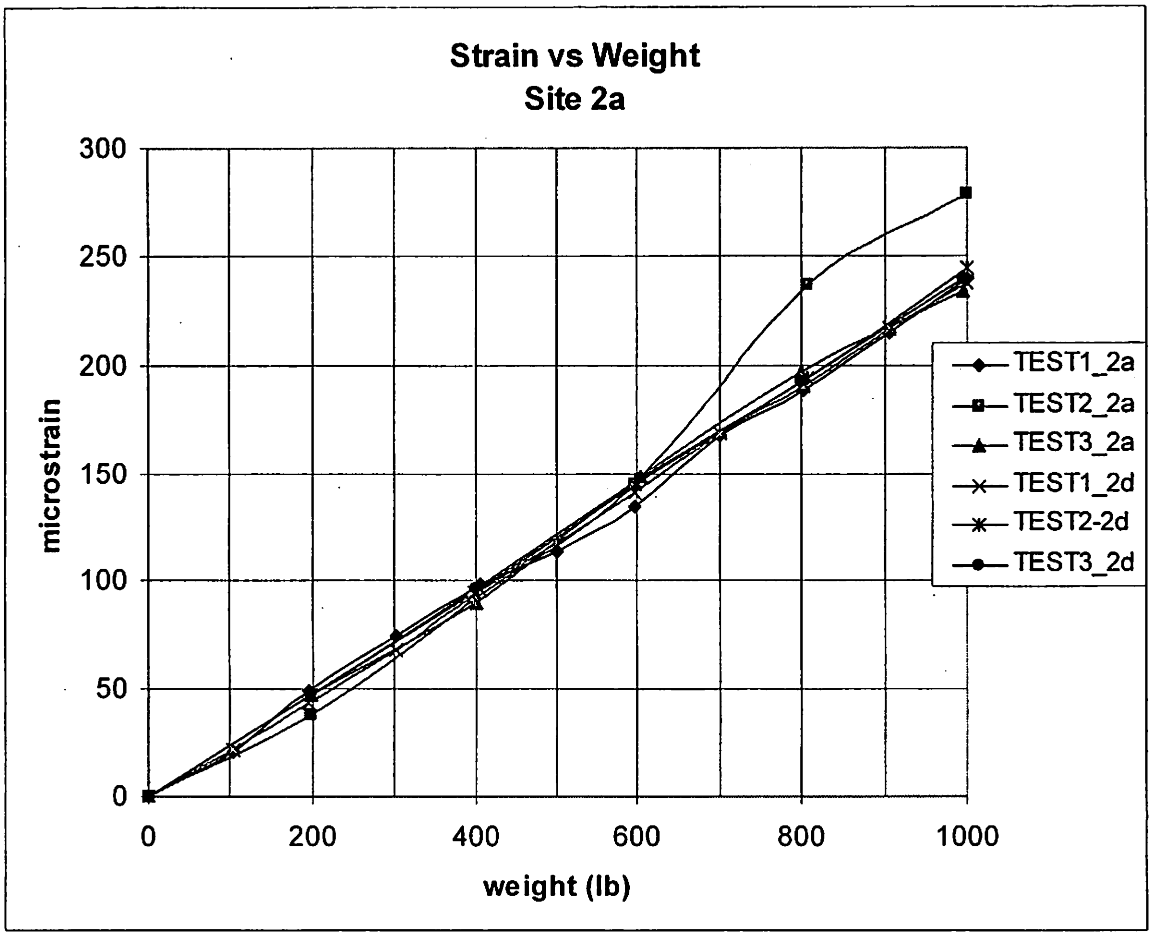
1c



weight	TEST1_1c	TEST2_1c	TEST3_1c	AVERAGE
0	0	0	0	**0.00**
100	2.5			**2.50**
200	11.5	17	11	**13.17**
300	18.5			**18.50**
400	22.5	23	21.5	**22.33**
500	27.5			**27.50**
600	36	36.5	36.5	**36.33**
700	42			**42.00**
800	46.5	46.5	47	**46.67**
900	52.5			**52.50**
1000	58.5	59.5	54	**57.33**

NOTE:
weight within 1% error

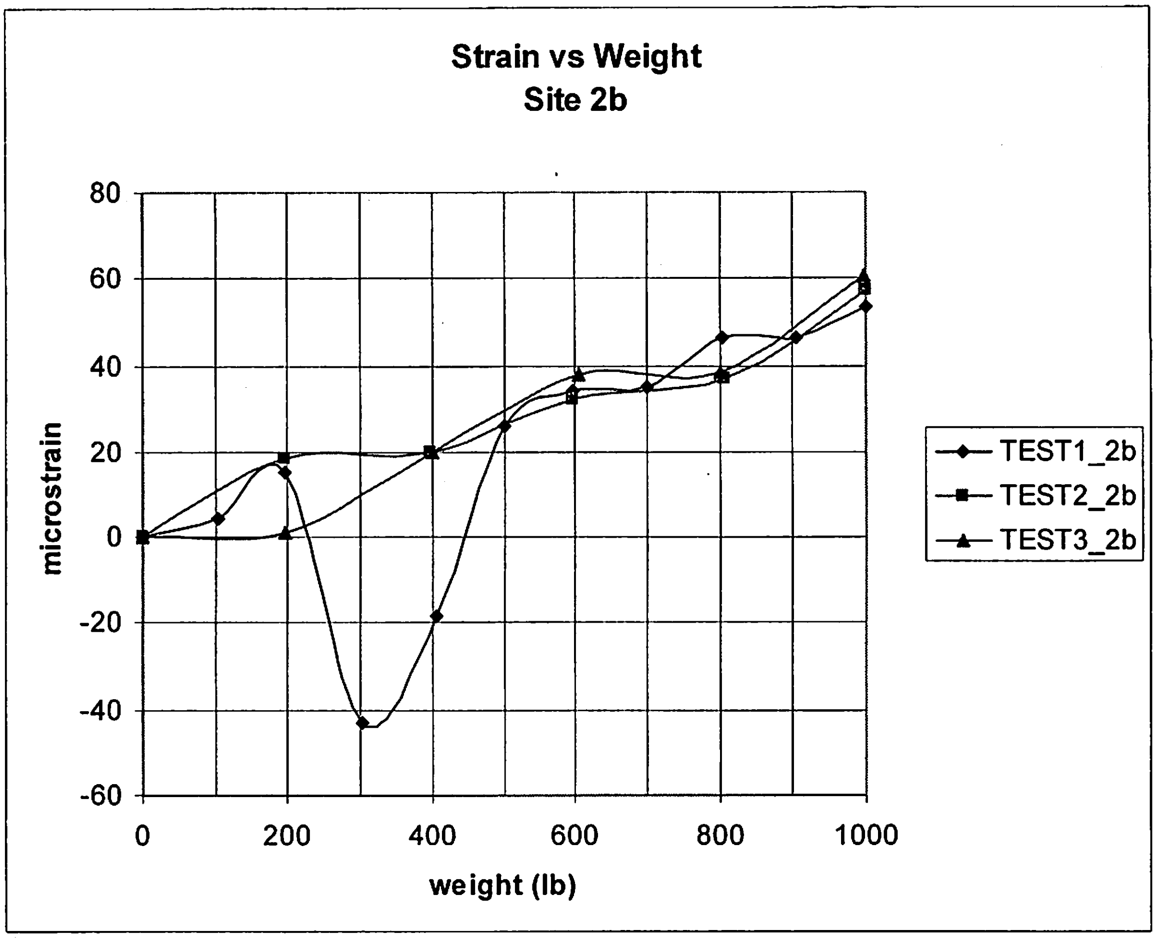
2a



weight	TEST1_2a	TEST2_2a	TEST3_2a	TEST1_2d	TEST2_2d	TEST3_2d	AVERAGE
0	0	0	0	0	0	0	**0.00**
100	20.5			22			**21.25**
200	49	38	47	43.5	47	47	**45.25**
300	75			68.5			**71.75**
400	98	92	90	96	95	96.5	**94.58**
500	114			117.5			**115.75**
600	134.5	145	148.5	141	145	147.5	**143.58**
700	167.5			168			**167.75**
800	188.5	237	196.5	190	194	192.5	**199.75**
900	214.5			216.5			**215.50**
1000	239	278.5	233.5	237.5	244.5	239	**245.33**

NOTE:
weight within 1% error

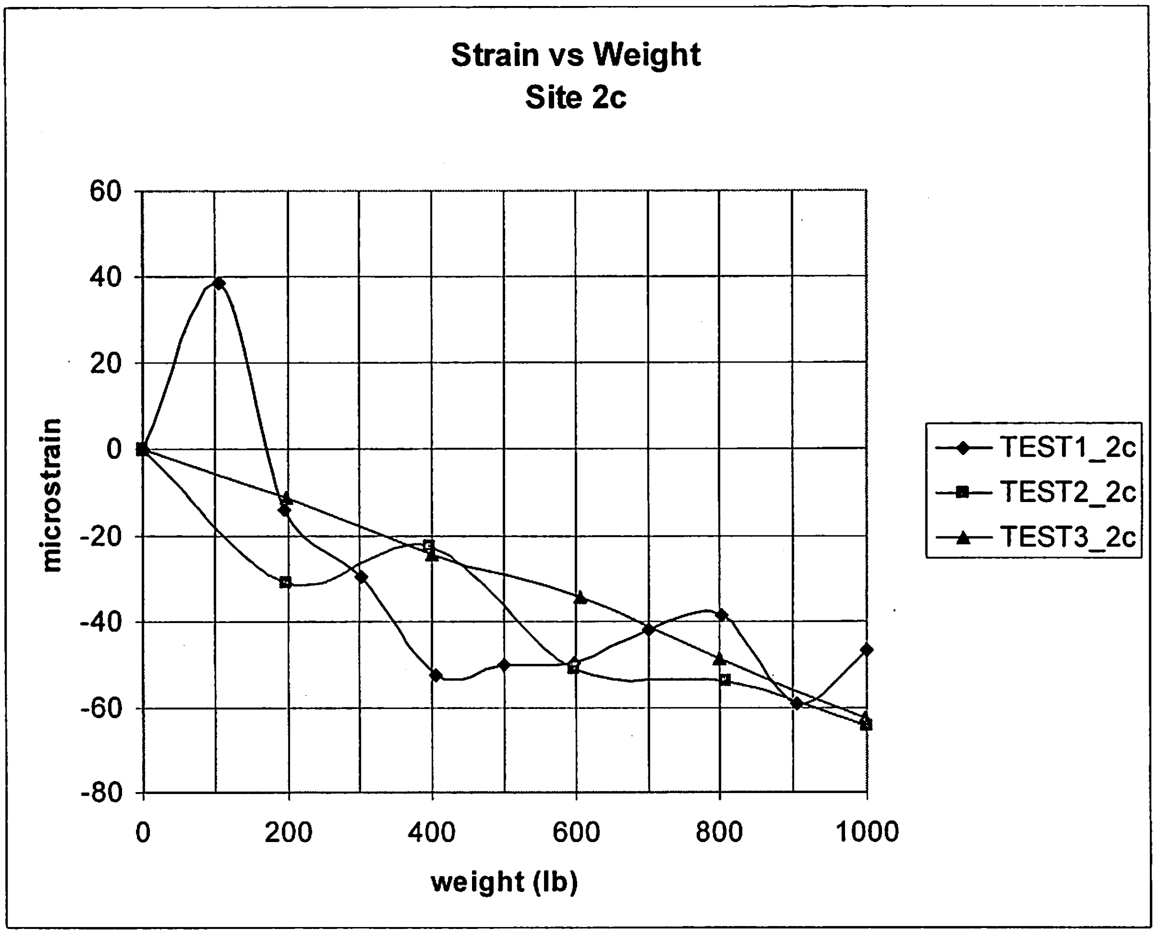
2b



weight	TEST1_2b	TEST2_2b	TEST3_2b	AVERAGE
0	0	0	0	**0.00**
100	38.5			**38.50**
200	-14	18.5	1	**1.83**
300	-29.5			**-29.50**
400	-52.5	20	20	**-4.17**
500	-50			**-50.00**
600	-49.5	32	38	**6.83**
700	-42			**-42.00**
800	-38.5	37	38.5	**12.33**
900	-59			**-59.00**
1000	-47	57.5	60.5	**23.67**

NOTE:
weight within 1% error

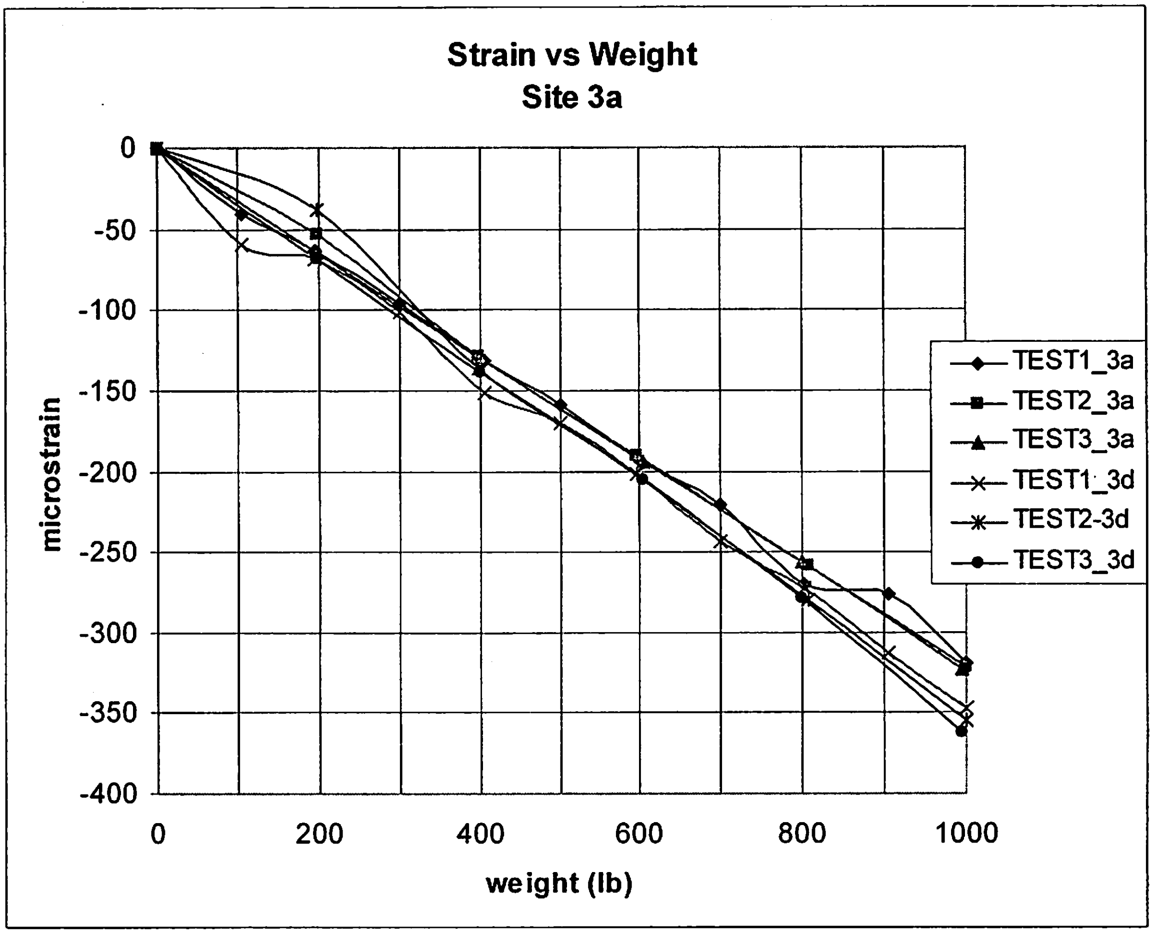
2c



weight	TEST1_2c	TEST2_2c	TEST3_2c	AVERAGE
0	0	0	0	**0.00**
100	38.5			**38.50**
200	-14	-31	-11	**-18.67**
300	-29.5			**-29.50**
400	-52.5	-22.5	-24.5	**-33.17**
500	-50			**-50.00**
600	-49.5	-51	-34.5	**-45.00**
700	-42			**-42.00**
800	-38.5	-54	-48.5	**-47.00**
900	-59			**-59.00**
1000	-47	-64.5	-62.5	**-58.00**

NOTE:
weight within 1% error

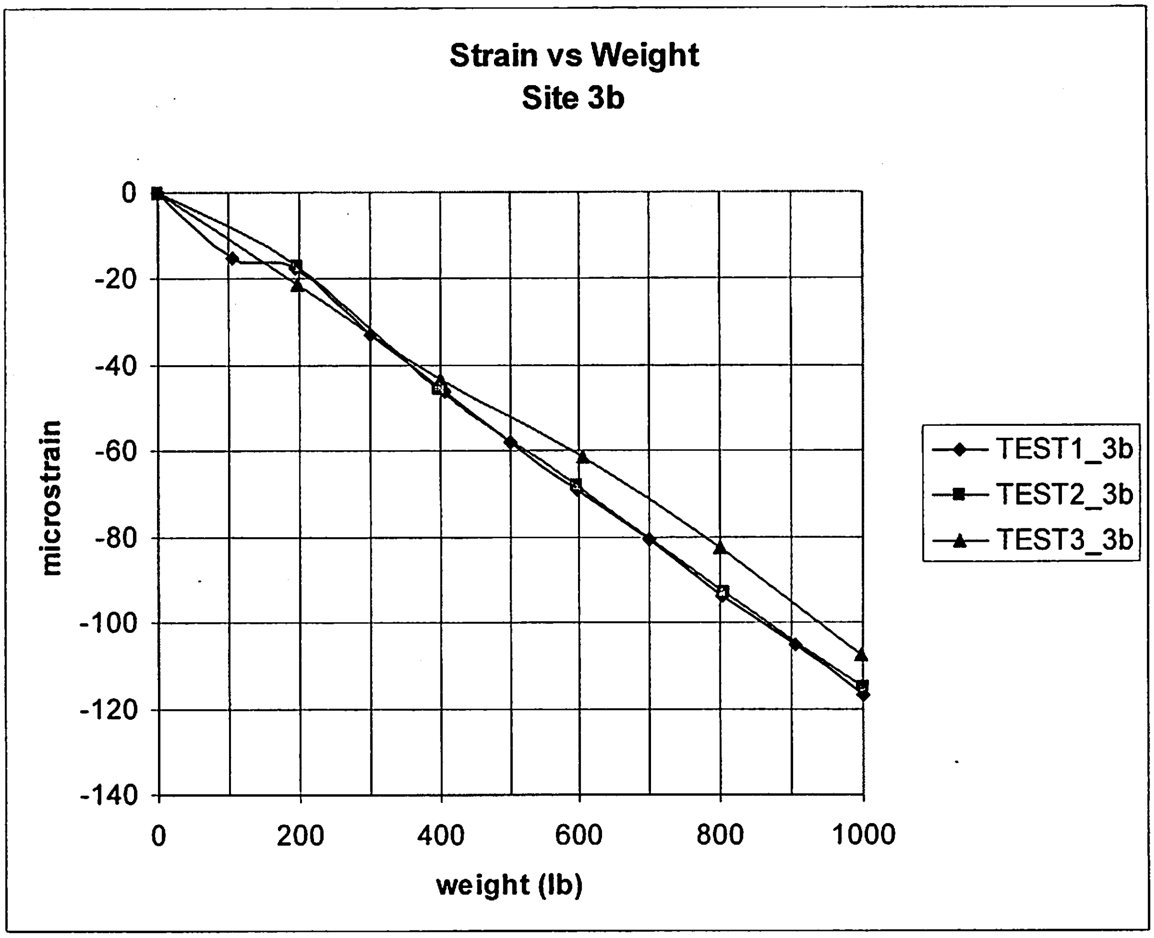
3a



weight	TEST1_3a	TEST2_3a	TEST3_3a	TEST1_3d	TEST2_3d	TEST3_3d	AVERAGE
0	0	0	0	0	0	0	**0.00**
100	-41			-59.5			**-50.25**
200	-63.5	-53	-64	-68	-37.5	-68	**-59.00**
300	-96.5			-101.5			**-99.00**
400	-131	-129	-129.5	-151.5	-136	-138.5	**-135.92**
500	-159			-170.5			**-164.75**
600	-192	-190.5	-194.5	-202.5	-202	-206	**-197.92**
700	-221			-243			**-232.00**
800	-269.5	-259	-256.5	-273	-280.5	-278.5	**-269.50**
900	-276.5			-312.5			**-294.50**
1000	-319.5	-322	-323.5	-347.5	-354.5	-362.5	**-338.25**

NOTE:
weight within 1% error

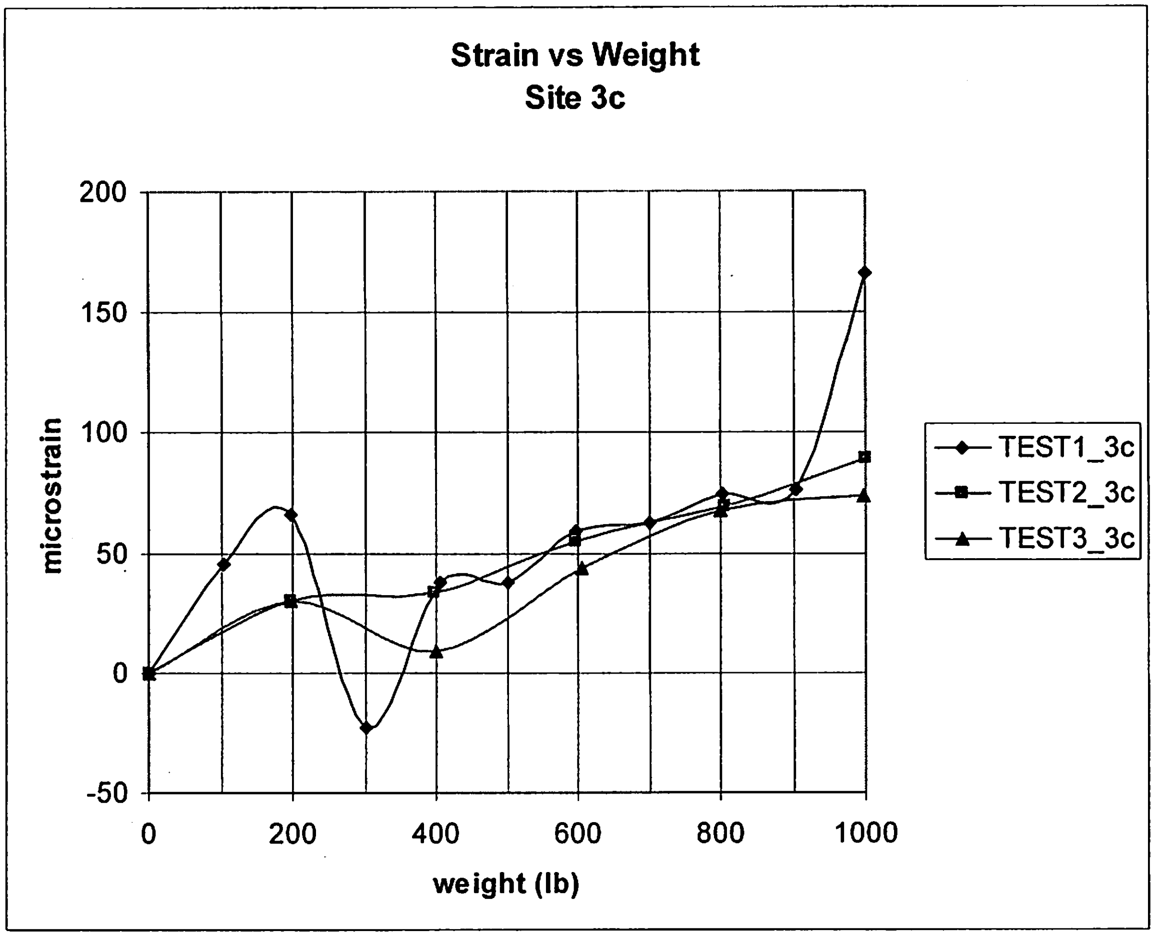
3b



weight	TEST1_3b	TEST2_3b	TEST3_3b	AVERAGE
0	0	0	0	**0.00**
100	-15			**-15.00**
200	-17.5	-17	-21.5	**-18.67**
300	-33			**-33.00**
400	-46.5	-46	-43.5	**-45.33**
500	-58			**-58.00**
600	-69	-68	-61.5	**-66.17**
700	-80.5			**-80.50**
800	-93.5	-92.5	-82.5	**-89.50**
900	-105			**-105.00**
1000	-117	-115	-107.5	**-113.17**

NOTE:
weight within 1% error

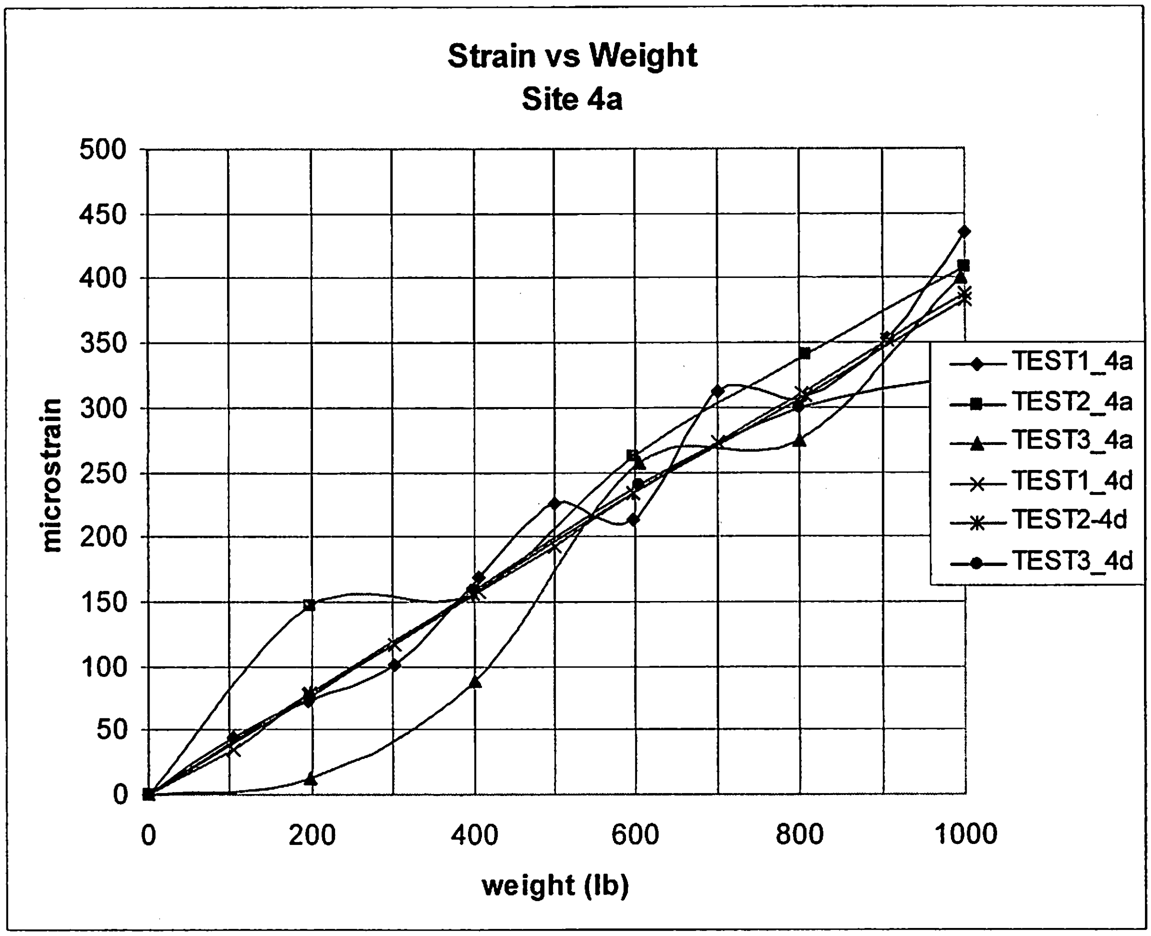
3c



weight	TEST1_3c	TEST2_3c	TEST3_3c	AVERAGE
0	0	0	0	**0.00**
100	46			**46.00**
200	66	30.5	30.5	**42.33**
300	-22.5			**-22.50**
400	38	33.5	9.5	**27.00**
500	38			**38.00**
600	59	55.5	44	**52.83**
700	63			**63.00**
800	74.5	69.5	67.5	**70.50**
900	76			**76.00**
1000	166.5	89	74	**109.83**

NOTE:
weight within 1% error

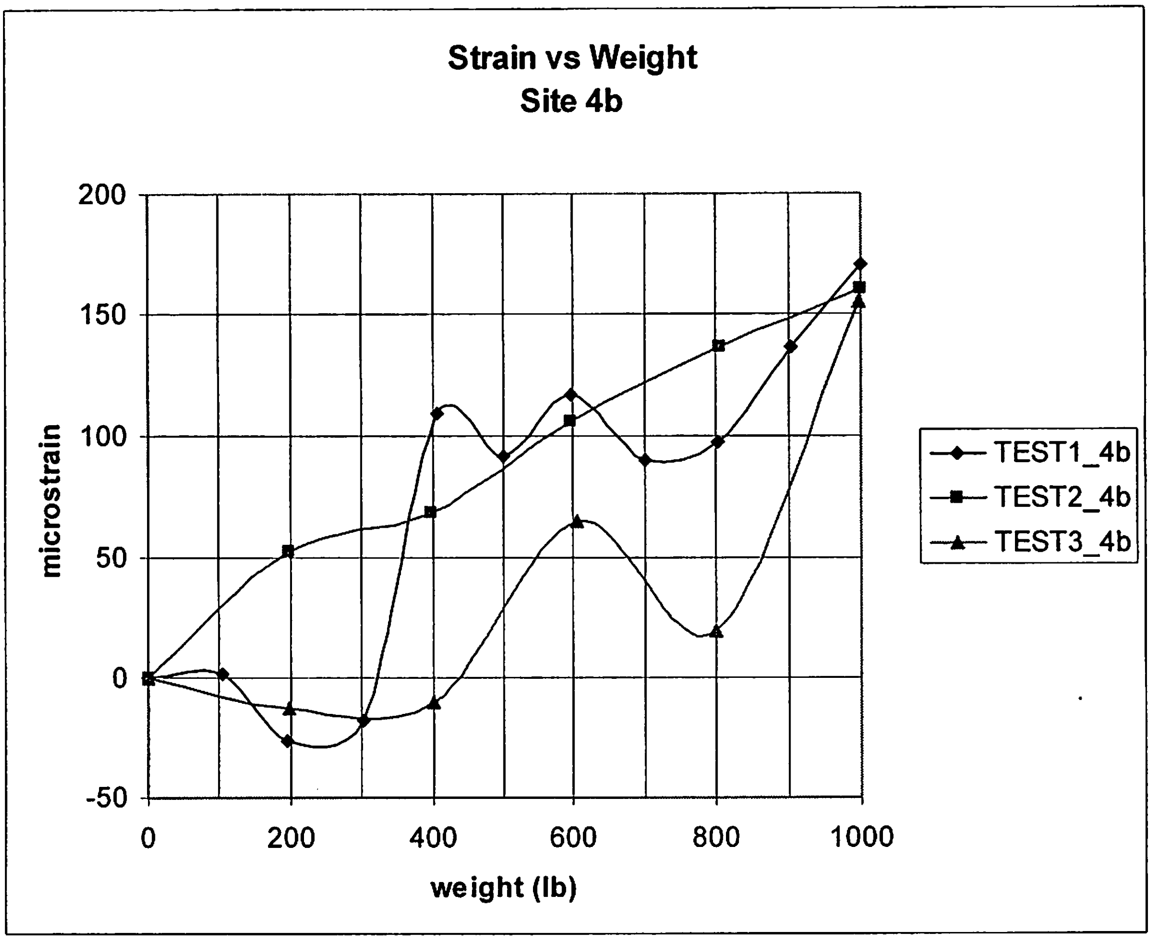
4a



weight	TEST1_4a	TEST2_4a	TEST3_4a	TEST1_4d	TEST2_4d	TEST3_4d	AVERAGE
0	0	0	0	0	0	0	**0.00**
100	43.5			34.5			**39.00**
200	72	147	12.5	76.5	79.5	75.5	**77.17**
300	100.5			116.5			**108.50**
400	169.5	155.5	89	158.5	156	159.5	**148.00**
500	226			193			**209.50**
600	213	261.5	257.5	233	233.5	240	**239.75**
700	312			272.5			**292.25**
800	308	341	275	310.5	309	299	**307.08**
900	354			351			**352.50**
1000	435.5	408	400	387.5	382.5	323	**389.42**

NOTE:
weight within 1% error

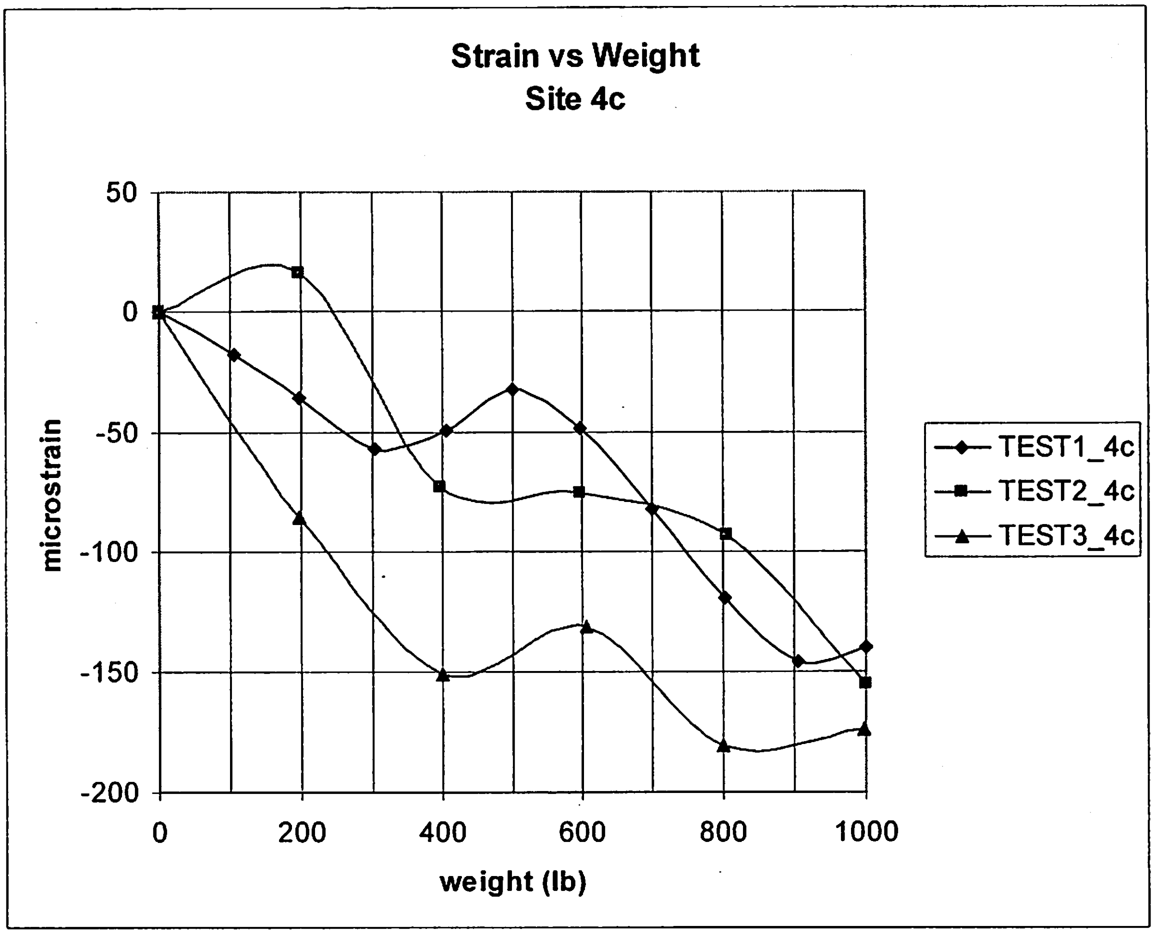
4b



weight	TEST1_4b	TEST2_4b	TEST3_4b	AVERAGE
0	0	0	0	**0.00**
100	1.5			**1.50**
200	-26.5	52.5	-13	**4.33**
300	-18			**-18.00**
400	110	68.5	-10	**56.17**
500	91.5			**91.50**
600	117	106	65	**96.00**
700	90			**90.00**
800	98	136.5	19	**84.50**
900	136.5			**136.50**
1000	170.5	160.5	155.5	**162.17**

NOTE:
weight within 1% error

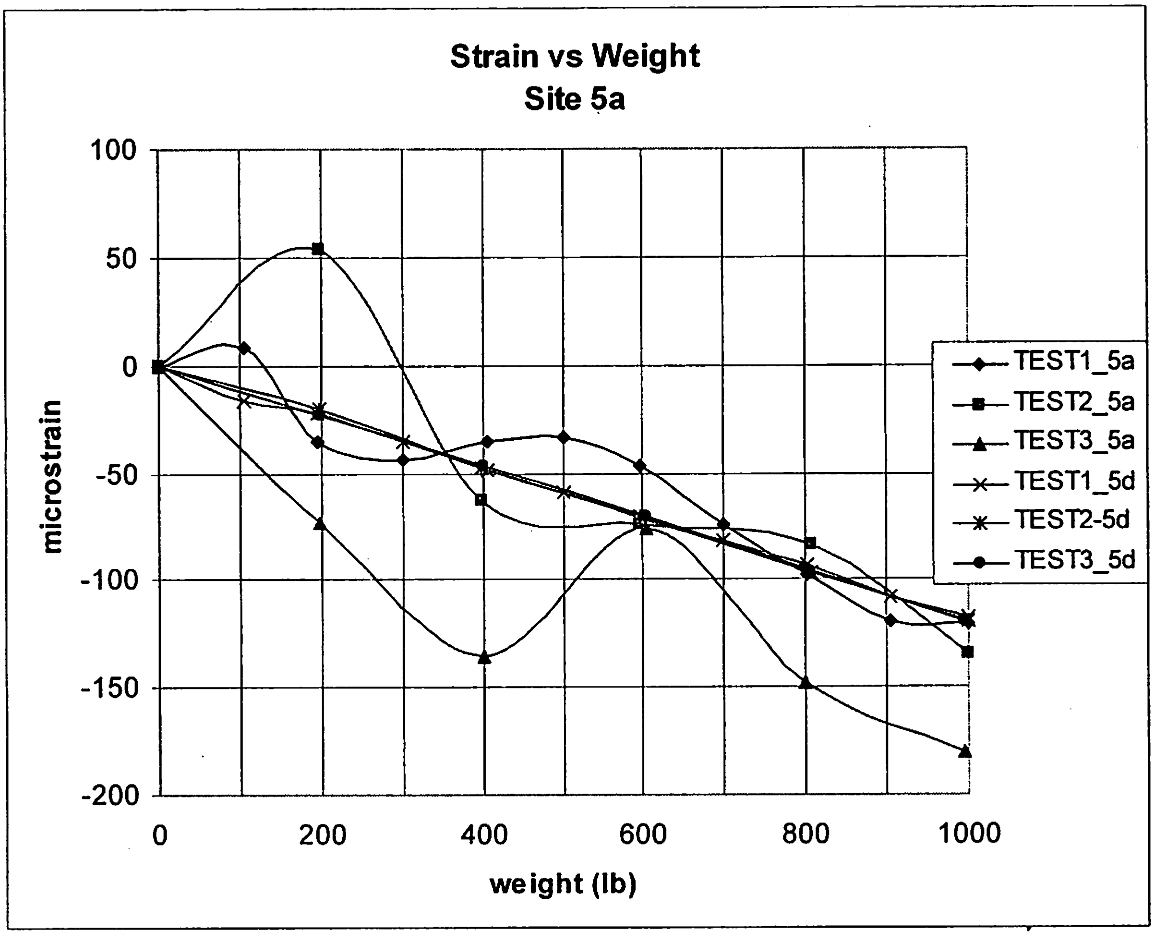
4c



weight	TEST1_4c	TEST2_4c	TEST3_4c	AVERAGE
0	0	0	0	**0.00**
100	-17.5			**-17.50**
200	-36	16.5	-86	**-35.17**
300	-57			**-57.00**
400	-49	-73	-150.5	**-90.83**
500	-32			**-32.00**
600	-48.5	-75	-131.5	**-85.00**
700	-82			**-82.00**
800	-119.5	-93.5	-180.5	**-131.17**
900	-145.5			**-145.50**
1000	-139.5	-155	-174	**-156.17**

NOTE:
weight within 1% error

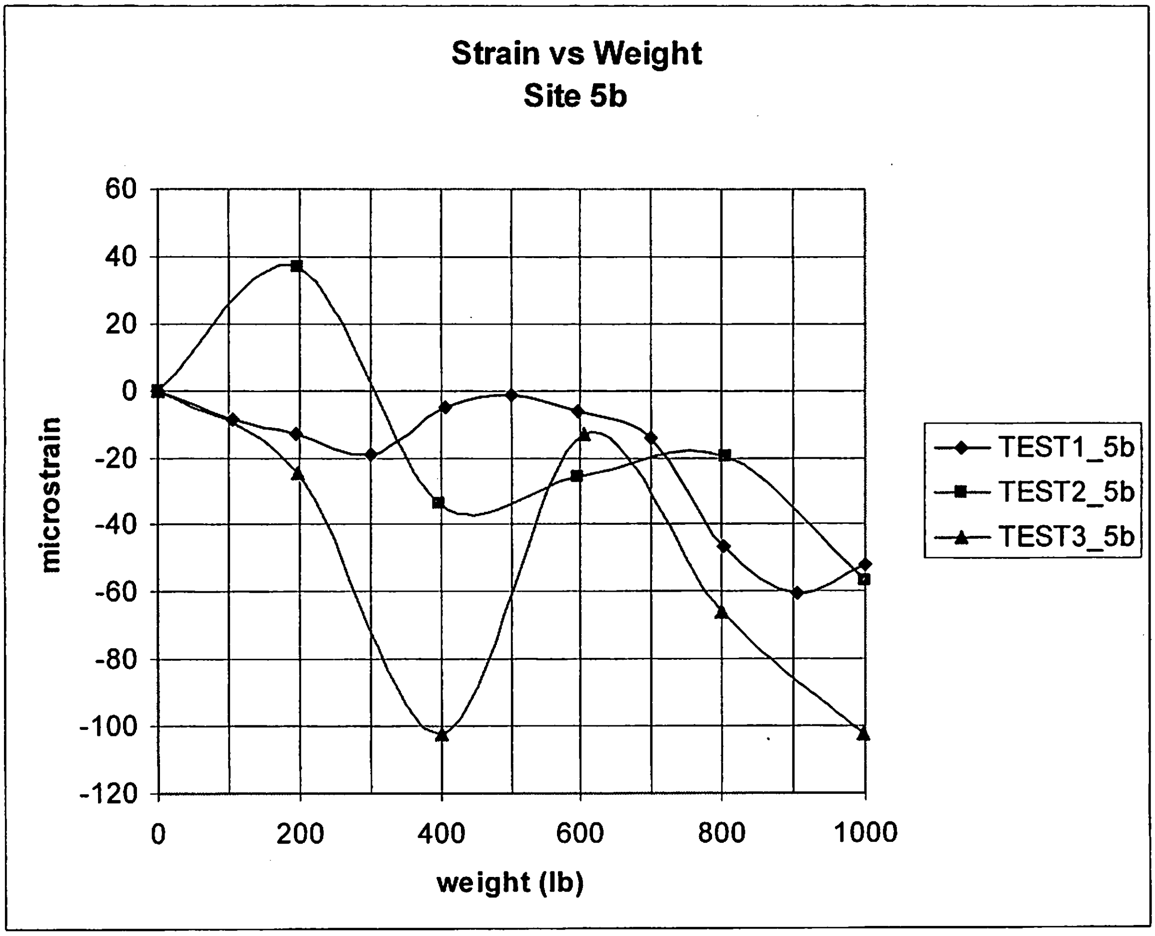
5a



weight	TEST1_5a	TEST2_5a	TEST3_5a	TEST1_5d	TEST2_5d	TEST3_5d	AVERAGE
0	0	0	0	0	0	0	**0.00**
100	8			-16.5			**-4.25**
200	-35	53.5	-73	-22.5	-20	-23.5	**-20.08**
300	-43.5			-35.5			**-39.50**
400	-35	-63	-135.5	-49	-47.5	-46.5	**-62.75**
500	-33.5			-59			**-46.25**
600	-46.5	-74.5	-76	-71.5	-70	-70	**-68.08**
700	-74.5			-82			**-78.25**
800	-98	-84	-148	-93.5	-96.5	-95	**-102.50**
900	-120			-108			**-114.00**
1000	-120.5	-134.5	-180.5	-118	-120	-119.5	**-132.17**

NOTE:
weight within 1% error

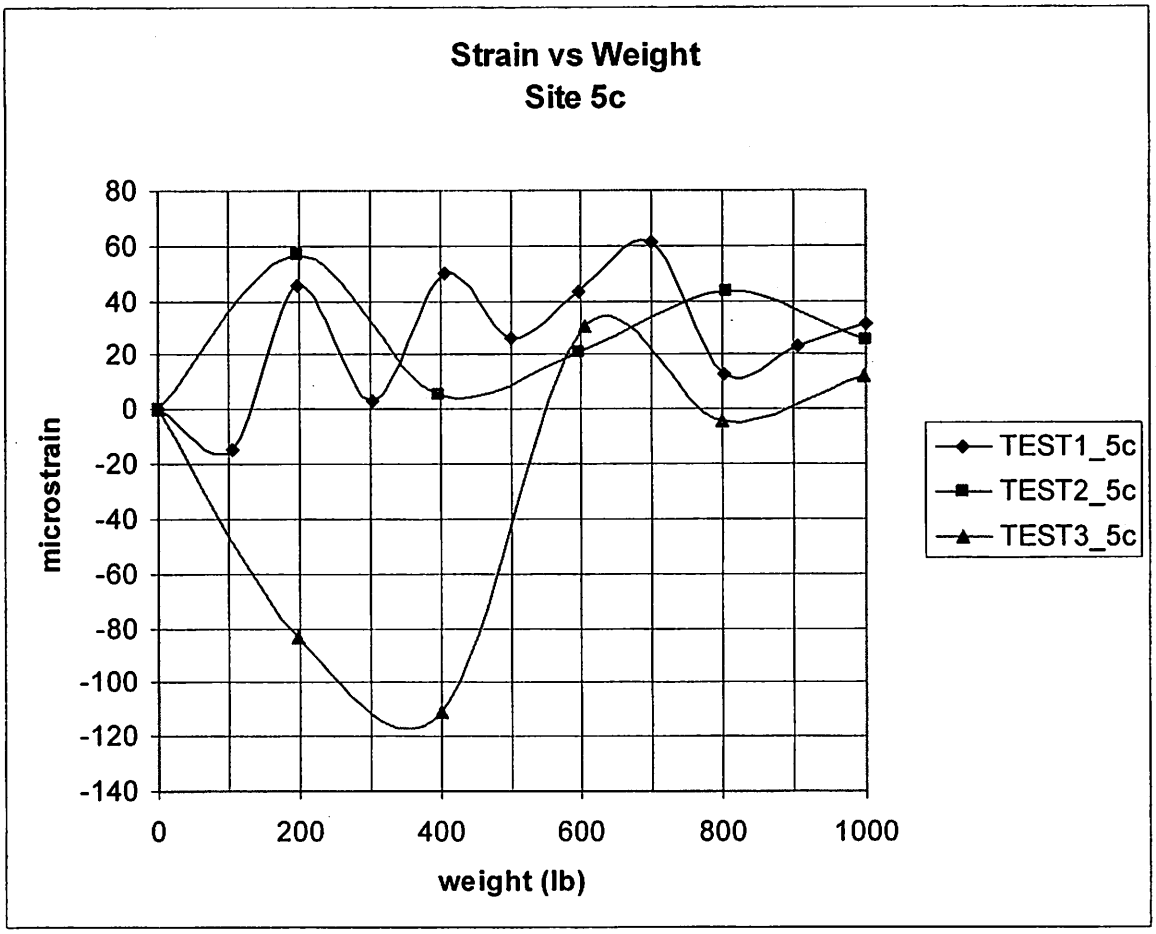
5b



weight	TEST1_5b	TEST2_5b	TEST3_5b	AVERAGE
0	0	0	0	**0.00**
100	-8.5			**-8.50**
200	-13	37	-24.5	**-0.17**
300	-19			**-19.00**
400	-5	-33.5	-102.5	**-47.00**
500	-1.5			**-1.50**
600	-6.5	-22.5	-13	**-14.00**
700	-14			**-14.00**
800	-46.5	-19.5	-66	**-44.00**
900	-60.5			**-60.50**
1000	-52	-56.5	-102.5	**-70.33**

NOTE:
weight within 1% error

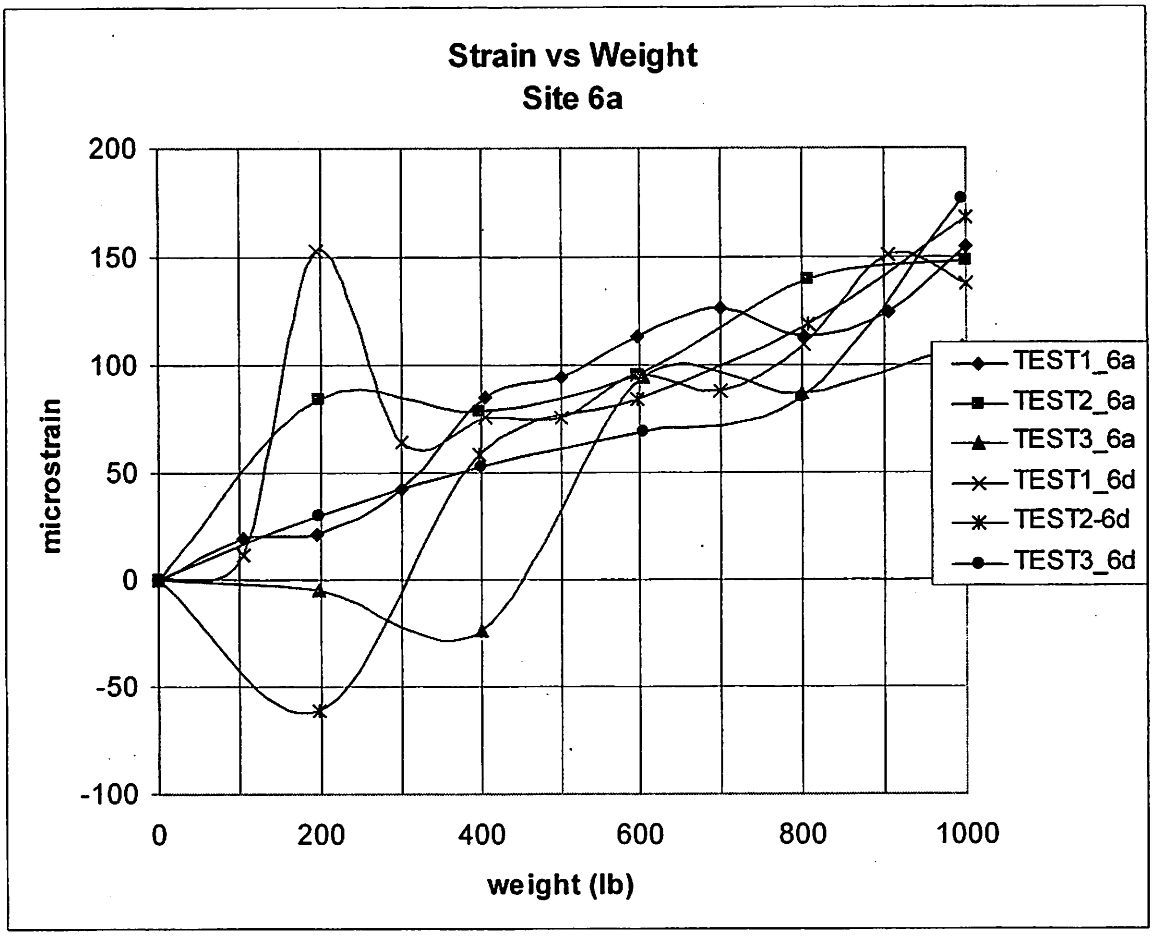
5c



weight	TEST1_5c	TEST2_5c	TEST3_5c	AVERAGE
0	0	0	0	**0.00**
100	-14.5			**-14.50**
200	45.5	57	-83	**6.50**
300	3.5			**3.50**
400	50.5	5.5	-111	**-18.33**
500	26			**26.00**
600	43.5	21	30.5	**31.67**
700	61.5			**61.50**
800	13	43.5	-4.5	**17.33**
900	23			**23.00**
1000	31.5	25.5	12.5	**23.17**

NOTE:
weight within 1% error

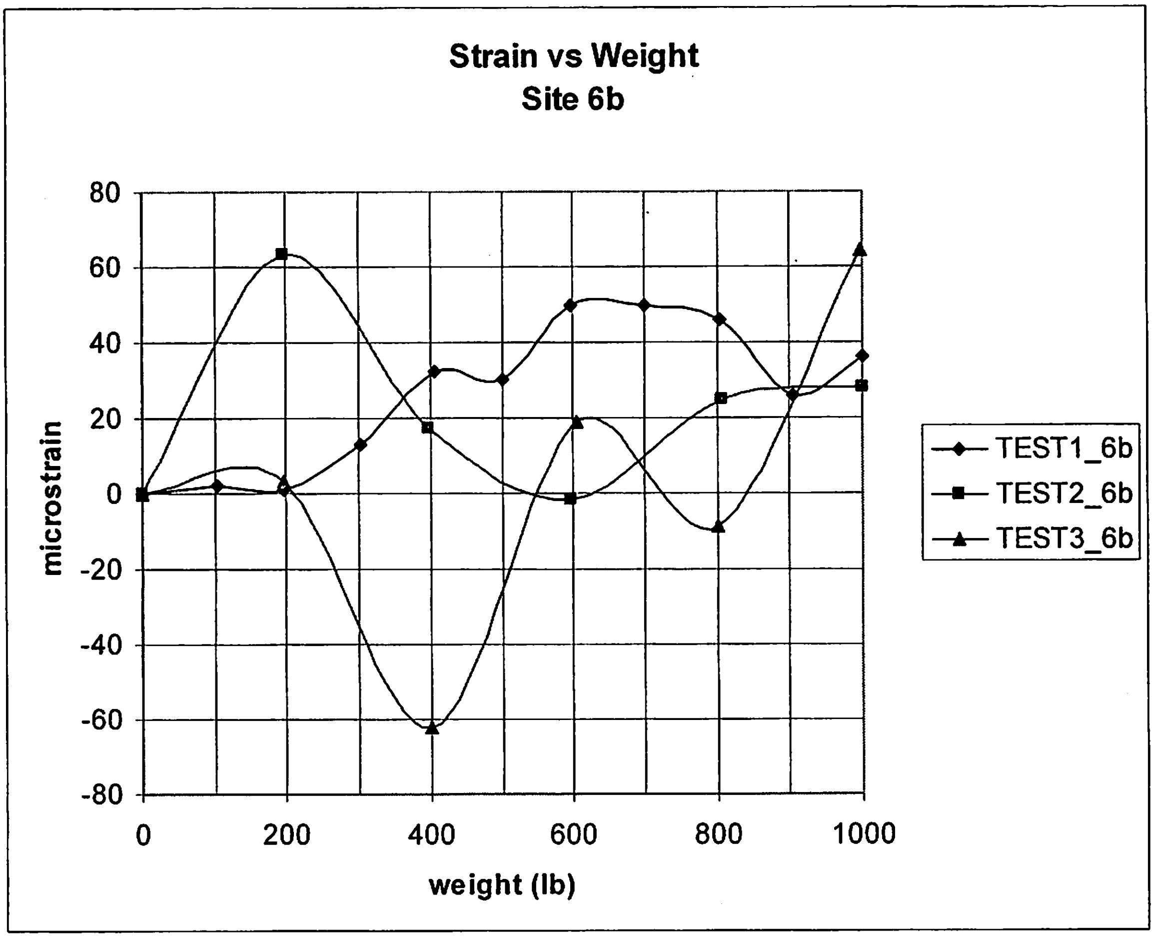
6a



weight	TEST1_6a	TEST2_6a	TEST3_6a	TEST1_6d	TEST2_6d	TEST3_6d	AVERAGE
0	0	0	0	0	0	0	**0.00**
100	19			12			**15.50**
200	21	83.5	-4.5	152.5	-61	29.5	**36.83**
300	41.5			63.5			**52.50**
400	84.5	78	-23.5	75	58.5	52.5	**54.17**
500	94			75			**84.50**
600	112.5	94.5	94	95	83.5	68	**91.25**
700	126.5			87			**106.75**
800	112.5	139.5	86	109.5	119	85	**108.58**
900	124.5			151			**137.75**
1000	154.5	148	108	138	168	176	**148.75**

NOTE:
weight within 1% error

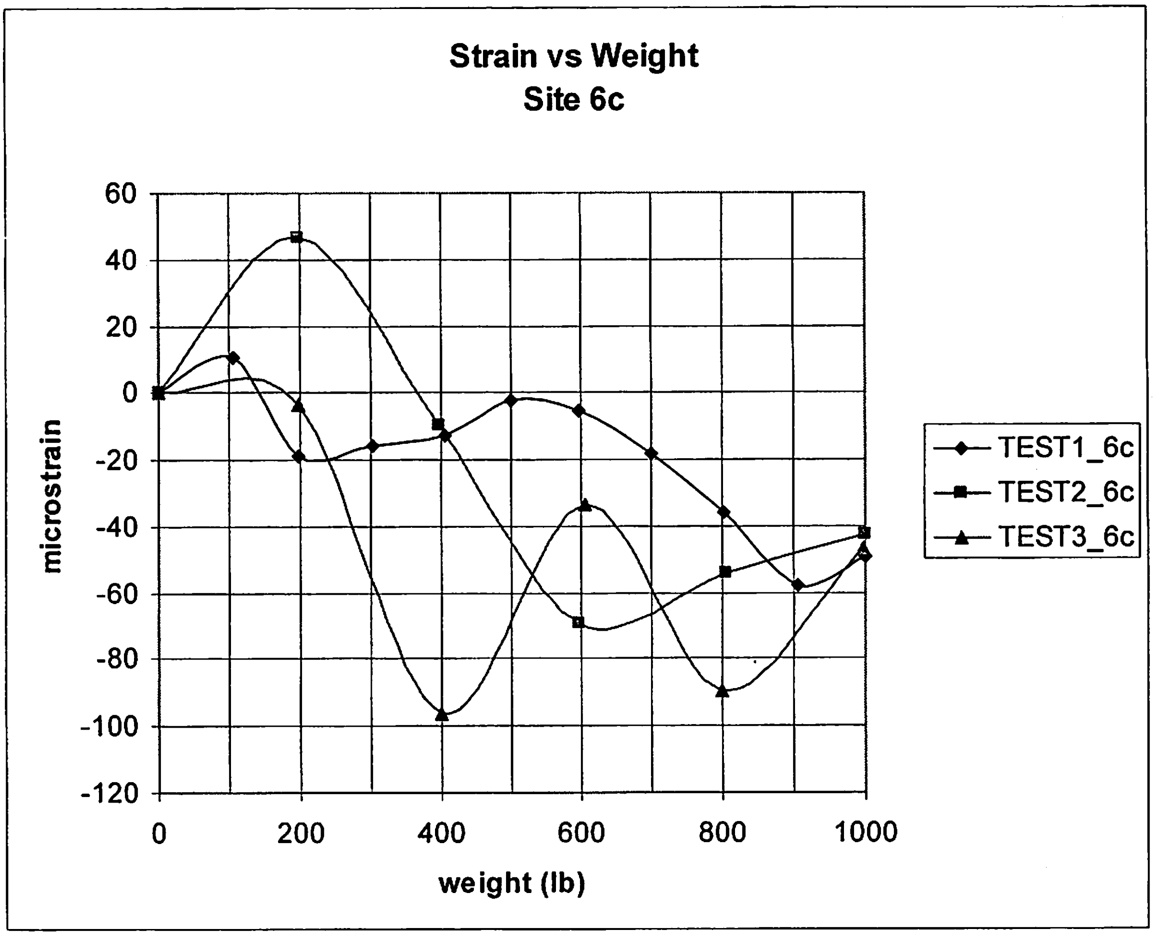
6b



weight	TEST1_6b	TEST2_6b	TEST3_6b	AVERAGE
0	0	0	0	**0.00**
100	2			**2.00**
200	1	63.5	3	**22.50**
300	13			**13.00**
400	32.5	17.5	-62	**-4.00**
500	30.5			**30.50**
600	50	-1.5	19	**22.50**
700	49.5			**49.50**
800	46	25	-8.5	**20.83**
900	26			**26.00**
1000	36	64.5	64.5	**55.00**

NOTE:
weight within 1% error

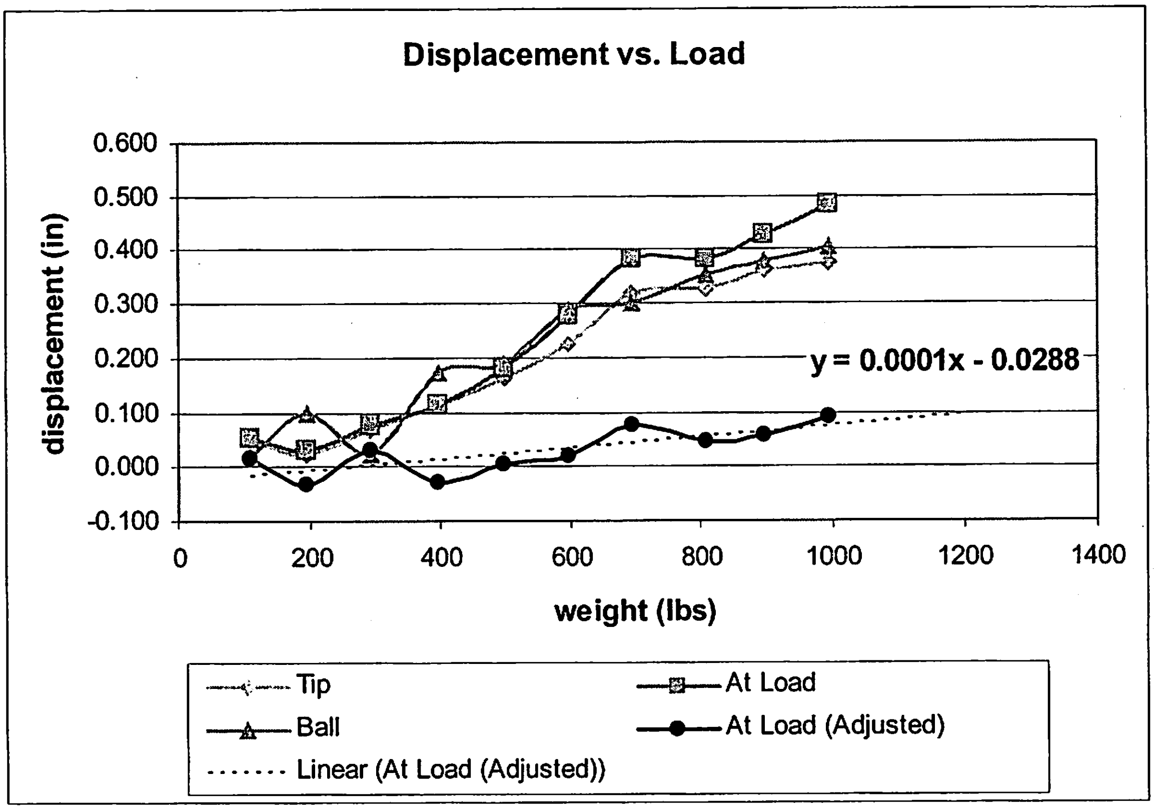
6c



weight	TEST1_6c	TEST2_6c	TEST3_6c	AVERAGE
0	0	0	0	**0.00**
100	10.5			**10.50**
200	-18.5	46.5	-3.5	**8.17**
300	-15.5			**-15.50**
400	-12.5	-9.5	-96	**-39.33**
500	-2.5			**-2.50**
600	-5.5	-69.5	-33.5	**-36.17**
700	-18			**-18.00**
800	-35.5	-54	-89.5	**-59.67**
900	-57.5			**-57.50**
1000	-49.5	-42.5	-47	**-46.33**

NOTE:
weight within 1% error

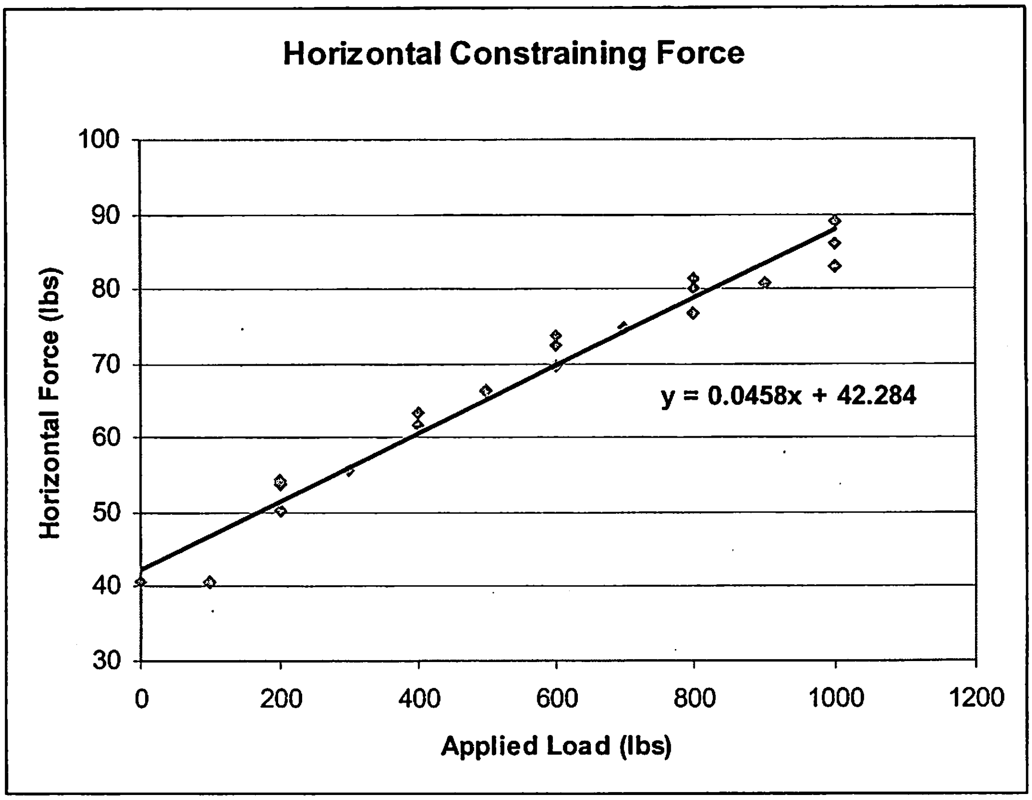
Displacement Results



Deflection Measurements (Corrected Data)

Position	Load (lbs)										
	0	109	196	292	398	498	597	696	808	897	995
Tip	0	0.050	0.024	0.070	0.114	0.163	0.226	0.319	0.325	0.362	0.375
At Load	0	0.052	0.030	0.076	0.113	0.181	0.279	0.384	0.384	0.429	0.483
Ball	0	0.019	0.099	0.023	0.172	0.189	0.290	0.299	0.353	0.380	0.407
At Load (Adjusted)	0	0.018	-0.032	0.030	-0.030	0.005	0.021	0.075	0.045	0.058	0.092

Horizontal Force Measurements



Test 1

Applied Load (lbs)	**0**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
Load Cell Output (V)	2.70	2.69	3.34	3.70	4.10	4.40	4.62	4.97	5.10	5.37	5.50
Tensile Force (lb)	40.68	40.55	50.31	55.78	61.81	66.33	69.65	74.93	76.89	80.96	82.92

Test 2

Applied Load (lbs)	**0**	**200**	**400**	**600**	**800**	**1000**
Load Cell Output (V)	2.70	3.57	4.20	4.90	5.40	5.90
Tensile Force (lb)	40.71	53.82	63.32	73.87	81.41	88.95

Test 3

Applied Load (lbs)	**0**	**200**	**400**	**600**	**800**	**1000**
Load Cell Output (V)	2.70	3.60	4.20	4.80	5.30	5.70
Tensile Force (lb)	40.71	54.27	63.32	72.36	79.90	85.93

SPECIFICATIONS

MODEL P-3500

Range:
±19,999με at Gauge Factor <6.000.
±6.000 x 19,999με at Gauge Factor >6.000.
GF

Above ranges increased by factor of 10 when using X10 multiplier switch. Example: ±199,990 at Gauge Factor <6.000.

Accuracy:
±0.5% of reading ±3με for Gauge Factor settings of 1.000 to 9.900.
±0.5% of reading ±20με for Gauge Factor settings of 1.000 to 9.900 when using X10 multiplier.

Sensitivity (Resolution):
±1με at all Gauge Factor settings.
±10με when using X10 multiplier.

Gauge Factor:
Range 0.500 to 9.900. Precisely settable to a resolution of 0.001 by 10-turn potentiometer and four-position switch. Gauge Factor accuracy ±0.02% at all settings. Displayed on digital readout.

Balance:
Coarse: 5 switch positions: Off, ±2,000με and ±4,000με (GF=2.000). Tolerance ±1% nominal.
Fine: 10-turn potentiometer with turns-counting dial, ±1,050με min. range (GF=2.000). Zero position of potentiometer calibrated for zero ±2με.
All balance voltages are electronically injected at input of amplifier. No bridge loading by balance controls and no compromise of measurement range.

Bridge Excitation:
2.0 Vdc ±0.1%. Temperature stability better than ±0.02% per °C. Readings are fully ratiometric and not degraded by variation in excitation voltage.

Bridge Configurations:
Quarter-, half- and full-bridge circuits. Internal bridge completion provided for 120/1,000Ω and 350Ω quarter bridges. 60 to 2,000Ω half or full bridges.

Amplifier:
Warm-up drift: Less than ±3 counts at GF=2.000, cold start to ten min.
Random drift at constant ambient temperature: Less than ±1 count at GF=2.000.
Common-mode rejection: Greater than 90 dB, 50 to 60 Hz.
Temperature effect on zero: Less than 1 μV/°C referred to input.
Temperature effect on span: Less than 0.005%/°C.
Input impedance: Greater than 30 MΩ.

Calibration:
Shunt calibration across 120Ω and 350Ω dummy gauges to simulate 5,000με (±0.05%).

Analog Output:
Linear ±2.50V max. Adjustable from 40 μV/με to 440 μV/με, nominal. Output load 2 KΩ min. Bandwidth, DC to 4 kHz, -3 dB nominal. Noise: Less than 400μV rms at 40 μV/με output level.

Remote Sense:
Provided at the transducer connector. Remote-sense error less than ±0.001%/Ω of lead resistance.

Power:
Internal battery pack using 6 "D" cells. Battery life 300 hours nominal (200 hours with LED readout).

Case:
Aluminum.

Size and Weight:
9 x 6 x 6 in *(228 x 152 x 152 mm)*. 6.3 lb. *(2.9 kg)* including batteries.

Accessories:
Line voltage adapter for 115V or 230V, 50 or 60 Hz, 60/30 mA.
Transducer input connector.

MODEL SB-10

(when used with Model P-3500)

Circuits:
10 channels plus OPEN position.

Inputs:
Will accept quarter-, half- or full-bridge circuits in any combination, including three-wire quarter bridges.

Balance Range:
Quarter and half bridge: ±2,000με with 350Ω half bridge in strain indicator.
Full bridge: ±2,000με for 350Ω bridge. Range proporational to bridge resistance.

Switching Repeatability:
Better than 1με.

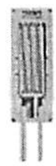
Size and Weight:
9 x 6 x 6 in *(228 x 152 x 152 mm)*. 5.5 lb. *(2.5 kg)*.

All specifications nominal or typical at +23°C unless noted.

Leaded Strain Gages for General-Purpose Applications

GAGE PATTERN Images may not be shown at actual size. ES = Each section CP = Complete pattern S = Section (S1 = Sec 1) M = Matrix (inch / millimeter)	GAGE DESIGNATION Insert desired S-T-C number in spaces marked XX.	RES. IN OHMS Tolerance is increased when Option W, E, SE, LE, or P is specified.	OPTIONS AVAILABLE

250LW

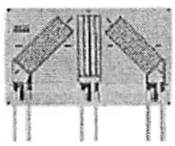


Widely used general-purpose gage.

GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.250	0.363	0.100	0.100
6.35	9.22	2.54	2.54
MATRIX SIZE	0.440L x 0.170W		11.18L x 4.32W

GAGE DESIGNATION	RES. IN OHMS	OPTIONS AVAILABLE
L2A-XX-250LW-120	120 ± 0.6%	
L2A-XX-250LW-350	350 ± 0.6%	

250LR

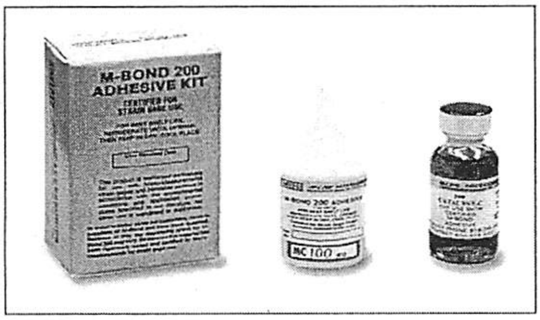


General-Purpose 45° rectangular single-plane rosette.

GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.250	0.373	0.100	0.655
6.35	9.47	2.54	16.64
MATRIX SIZE	0.420L x 0.715W		10.67L x 18.16W

GAGE DESIGNATION	RES. IN OHMS	OPTIONS AVAILABLE
L2A-XX-250LR-120	120 ± 0.6%	
L2A-XX-250LR-350	350 ± 0.6%	

Strain Gage Adhesive



OTHER ACCESSORIES USED IN AN M-BOND 200 INSTALLATION:

- CSM Degreaser or GC-6 Isopropyl Alcohol
- Silicon Carbide Paper
- M-Prep Conditioner A
- M-Prep Neutralizer 5A
- GSP-1 Gauze Sponges
- CSP-1 Cotton Applicators
- PCT-2M Gage Installation Tape

DESCRIPTION

For routine experimental stress analysis applications under temperate environmental conditions, M-Bond 200 adhesive is ordinarily the best choice. This adhesive is very easy to handle, and cures almost instantly to produce an essentially creep-free, fatigue-resistant bond, with elongation capability of five percent or more.

M-Bond 200 is a cyanoacrylate that has been pretested and certified for use in bonding strain gages. It is an excellent general-purpose adhesive for laboratory and short-term field applications. The procedure for making a strain gage installation with M-Bond 200 is illustrated and described in detail in Instruction Bulletin B-127 included in each kit of adhesive.

The user should note that the performance of the adhesive can be degraded by the effects of time, humidity conditions, elevated temperature, and moisture absorption. Because of the latter effect, strain gage installations should always be covered with a suitable protective coating. When necessitated by more rigorous test requirements and/or environmental conditions, consideration should be given to one of the M-Bond epoxy adhesives, using the "Recommended Adhesives/Strain Gage Series" chart.

CHARACTERISTICS

Cure Requirements:
One-minute thumb pressure, followed by a minimum two-minute delay before tape removal. Bond strength increases rapidly during first five minutes. Cure time must be extended under conditions of low temperature (<70°F [<21°C]) or low humidity (<40% RH).

Operating Temperature Range:
Short Term: –300° to +200°F [–185° to +95°C].
Long Term: –25° to +150°F [–32° to +65°C].

Elongation Capabilities:
>5% at +75°F [+24°C], 3% at +75°F [+24°C] when used with CEA or EA/Option E strain gages.

Shelf Life:
3 months at +75°F [+24°C] after opening, with cap replaced immediately after each use. Shelf life refers to the duration of time, beginning on date of shipment, over which properly stored adhesive should be expected to meet published specifications.

Note: To ensure a proper seal, wipe bottle spout clean and dry before replacing cap.

May be stored unopened up to 3 months at +75°F [+24°C] or 6 months at +40°F [+5°C].

Note: Condensation rapidly degrades adhesive performance and shelf life; after refrigeration, allow adhesive to reach room-temperature before opening. Refrigeration after opening is not recommended.

PACKAGING OPTIONS

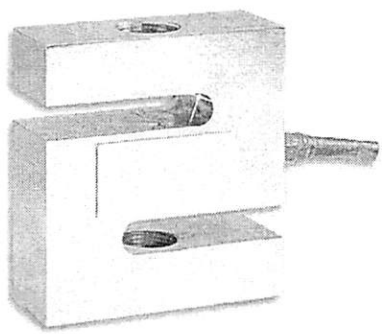
Kit:
1 bottle [1 oz/28 g] Adhesive
1 brush-cap bottle [30 ml] Catalyst
polyethylene dispenser cap

Bulk:
Adhesive — 16 bottles [1 oz/28 g each]
Catalyst — 12 brush-cap bottles [30 ml each]

0-5000 lb Load Cell

LC101-5K
S/N: 109773

Loads read via an
AMDI Transducer Indicator
Model 1601C



SPECIFICATIONS

Excitation: 10 Vdc, 15 Vdc max
Output: 3 mV/V ±.0075 mV/V
Linearity: ±0.03% FSO (0.1% 40 K)
Hysteresis: ±0.02% FSO(0.1% 40 K)
Repeatability: ±0.01% FSO (0.05% 40 K)
Zero Balance: ±1% FSO
Agency Approval: FM Intrinsically Safe IS/I.II.III/1/CDEFG - Standard
Operating Temp Range: -40 to +93°C (-40 to 200°F)
Compensated Temp Range: 17 to 71°C (60 to 160°F)
Thermal Effects: Zero: 0.001% FSO/°F Span: 0.001%FSO/°F
Safe Overload: 150% of Capacity
Ultimate Overload: 300% of Capacity
Input Resistance: 350 ±10 Ohms
Output Resistance: 350 ±10 Ohms
Full Scale Deflection: 0.010 to 0.020"
Construction: 17-4 PH Stainless Steel
Electrical: LC101: up to 200 lb = 30 ft 24 AWG; 250-2000 lb = 30 ft 20 AWG; 3000 lb and up= 15 ft 20 AWG 4-conductor shielded cable, LC111:up to 200 lbs 4 pin connector mating connector: PT06F8-4S (not included) >200 lbs, 6 pin connector, mating connector: PT06F10-6S (not included)

Horizontal Reaction Force Load Cell
112 lb
Model: SMT2-112-10
S/N: E39189

interface

Model SMT Series (U.S. & Metric)

Why Interface SMT load cells are the best in class:

- Proprietary Interface temperature compensated strain gages
- Overload protected in both tension and compression
- Safe overload to 10 times capacity
- Highest accuracy
- Low creep
- 1 to 450 lbf

SPECIFICATIONS

ACCURACY – (MAX ERROR)

Nonlinearity–% FS .... ±0.05
Hysteresis–% FS .... ±0.03
Nonrepeatability–% RO .... ±0.02
Creep, in 20 min.–% .... ±0.025

TEMPERATURE

Compensated Range– F .... 0 to 125
Compensated Range– C .... -15 to 50
Operating Range– F .... -10 to 175
Operating Range– C .... -25 to 80
Effect on Output–%/°F – MAX .... ±0.0010
Effect on Output–%/°C – MAX .... ±0.0018
Effect on Zero–% RO/°F – MAX .... ±0.0015
Effect on Zero–% RO/°C – MAX .... ±0.0027

ELECTRICAL

Rated Output–mV/V (Nominal) 2.0
Zero Balance–% RO .... ±3.0
Bridge Resistance–Ohm (Nominal) 350
Excitation Voltage – MAX .... 15 VDC
Insulation Resistance–Megohm 5000

MECHANICAL

Calibration .... T & C
Safe Overload–% CAP (1.1, 2.2, 5.6, 11, 22, 56) ..1000
(112, 225, 450) 500
Cable length–ft 5

Natural Frequency/Deflection:

lbf	N	Deflection (inches)	Nat. Freq. (Hertz)
1.1	5	.014	100
2.2	10	.012	160
5.6	25	.011	280
11	50	.009	380
22	100	.007	600
56	250	.005	900
112	500	.007	600
225	1000	.007	1200
450	2000	.007	1500

STANDARD CONFIGURATION

- 5 Ft Integral Cable (SMT1-nn up to 22lbf or 100N) <or> 5 Ft Integral Cable (SMT2-nn 112 to 450lbf or 500N to 2000N)

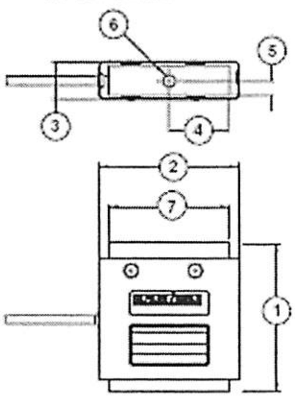
*OPTIONS

Alternate cable length
Standardized output

*ACCESSORIES

Instrumentation
Mounting hardware

* See appendix for more technical information



DIMENSIONS

See Drawing	CAPACITY			
	SMT1		SMT2	
	U.S. (lbf)	Metric (N)	U.S. (lbf)	Metric (N)
	1.1, 2.2, 5.6, 11, 22, 56	5, 10, 25, 50, 100, 250	112, 225, 450	500, 1000, 2000
	inch	mm	inch	mm
①	2.48	63.0	2.98	75.7
②	2.33	59.2	2.33	59.2
③	0.65	16.5	1.15	29.2
④	0.98	24.9	0.98	24.9
⑤	0.24	6.1	0.49	12.4
⑥	1/4-28 UNF-3B	M6 x 1-6H	1/2-20 UNF-3B	M12 x 1.75-6H
	0.31 deep	8.0 deep	0.57 deep	14.5 deep
⑦	1.96	49.8	1.96	49.8

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01/02

VISHAY

Instruction Bulletin B-127-14
Vishay Micro-Measurements

Strain Gage Installations with M-Bond 200 Adhesive

INTRODUCTION

Micro-Measurements Certified M-Bond 200 is an excellent general-purpose laboratory adhesive because of its fast room-temperature cure and ease of application. When properly handled and used with the appropriate strain gage, M-Bond 200 can be used for high-elongation tests in excess of 60 000 microstrain, for fatigue studies, and for one-cycle proof tests to over +200°F [+95°C] or below −300°F [−185°C]. The normal operating temperature range is −25° to +150°F [−30° to +65°C]. M-Bond 200 is compatible with all Micro-Measurements strain gages and most common structural materials. When bonding to plastics, it should be noted that for best performance the adhesive flowout should be kept to a minimum. For best reliability, it should be applied to surfaces between the temperatures of +70° and +85°F [+20° to +30°C], and in a relative humidity environment of 30% to 65%.

M-Bond 200 catalyst has been specially formulated to control the reactivity rate of this adhesive. The catalyst should be used sparingly for best results. Excessive catalyst can contribute many problems; e.g., poor bond strength, age-embrittlement of the adhesive, poor glueline thickness control, extended solvent evaporation time requirements, etc.

Since M-Bond 200 bonds are weakened by exposure to high humidity, adequate protective coatings are essential. This adhesive will gradually become harder and more brittle with time, particularly if exposed to elevated temperatures. For these reasons, M-Bond 200 is not generally recommended for installations exceeding one or two years.

For proper results, the procedures and techniques presented here should be used with qualified Micro-Measurements installation accessory products (refer to Catalog A-110). Those used in this procedure are:

CSM Degreaser or GC-6 Isopropyl Alcohol
Silicon Carbide Paper
M-Prep Conditioner A
M-Prep Neutralizer 5A
GSP-1 Gauze Sponges
CSP-1 Cotton Applicators
PCT-2A Cellophane Tape

Various installation techniques are described on professionally prepared videotapes available from Vishay Measurements Group. Request Bulletin 318 for details.

SHELF AND STORAGE LIFE

M-Bond 200 adhesive has a shelf life of three months at +75°F [+24°C] after opening and with the cap placed back onto the bottle immediately after each use. Note: To ensure the cap provides a proper seal, the bottle spout should be wiped clean and dry before replacing the cap.

Unopened M-Bond 200 adhesive may be stored up to three months at +75°F [+24°C] or six months at +40°F [+5°C].

Note: Condensation will rapidly degrade adhesive performance and shelf life: after refrigeration the adhesive must be allowed to reach room temperature before opening, and refrigeration after opening is not recommended.

HANDLING PRECAUTIONS

M-Bond 200 is a modified alkyl cyanoacrylate compound. Immediate bonding of eye, skin or mouth may result upon contact. Causes irritation. The user is cautioned to: (1) avoid contact with skin; (2) avoid prolonged or repeated breathing of vapors; and (3) use with adequate ventilation. For additional health and safety information, consult the Material Safety Data Sheet which is available upon request.

GAGE APPLICATION TECHNIQUES

The installation procedure presented on the following pages is somewhat abbreviated and is intended only as a guide in achieving proper gage installation with M-Bond 200. Vishay Measurements Group Application Note B-129 presents recommended procedures for surface preparation, and lists specific considerations which are helpful when working with most common structural materials.

Step 1
Thoroughly degrease the gaging area with solvent, such as CSM Degreaser or GC-6 Isopropyl Alcohol (Figure 1). The former is preferred, but there are some materials (e.g., titanium and many plastics) that react with chlorinated solvents. In these cases, GC-6 Isopropyl Alcohol should be considered. All degreasing should be done with uncontaminated solvents—thus the use of "one-way" containers, such as aerosol cans, is highly advisable.

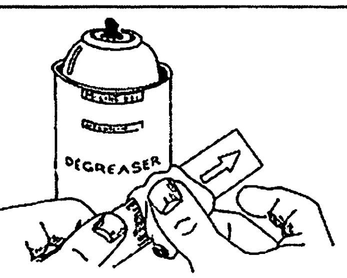


Figure 1

Strain Gage Installations with M-Bond 200 Adhesive

Step 2
Preliminary dry abrading with 220- or 320-grit silicon-carbide paper (Figure 2a) is generally required if there is any surface scale or oxide. Final abrading is done by using 320-grit silicon-carbide paper on surfaces thoroughly wetted with M-Prep Conditioner A; this is followed by wiping dry with a gauze sponge. Repeat this wet abrading process with 400-grit silicon-carbide paper, then dry by slowly wiping through with a gauze sponge, as in Figure 2b.

Using a 4H pencil (on aluminum) or a ballpoint pen (on steel), burnish (do not scribe) whatever alignment marks are needed on the specimen. Repeatedly apply M-Prep Conditioner A and scrub with cotton-tipped applicators until a clean tip is no longer discolored. Remove all residue and Conditioner by again slowly wiping through with a gauze sponge. Never allow any solution to dry on the surface because this invariably leaves a contaminating film and reduces chances of a good bond.

Step 3
Now apply a liberal amount of M-Prep Neutralizer 5A and scrub with a cotton-tipped applicator. See Figure 3. With a single, slow wiping motion of a gauze sponge, carefully dry this surface. Do not wipe back and forth because this may allow contaminants to be redeposited.

Step 4
Using tweezers to remove the gage from the transparent envelope, place the gage (bonding side down) on a chemically clean glass plate or gage box surface. If a solder terminal will be used, position it on the plate adjacent to the gage as shown. A space of approximately 1/16 in [1.6 mm] should be left between the gage backing and terminal. Place a 4- to 6-in [100- to 150-mm] piece of Micro-Measurements No. PCT-2A cellophane tape over the gage and terminal. Take care to center the gage on the tape. Carefully lift the tape at a shallow angle (about 45 degrees to specimen surface), bringing the gage up with the tape as illustrated in Figure 4.

Step 5
Position the gage/tape assembly so that the triangle alignment marks on the gage are over the layout lines on the specimen (Figure 5). If the assembly appears to be misaligned, lift one end of the tape at a shallow angle until the assembly is free of the specimen. Realign properly, and firmly anchor at least one end of the tape to the specimen. Realignment can be done without fear of contamination by the tape mastic if Micro-Measurements No. PCT-2A cellophane tape is used, because this tape will retain its mastic when removed.

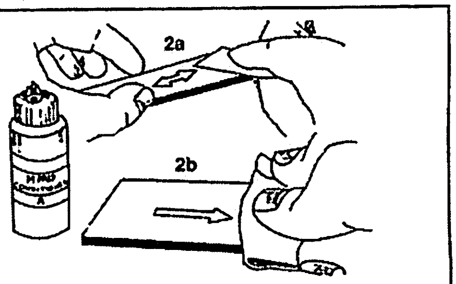


Figure 2

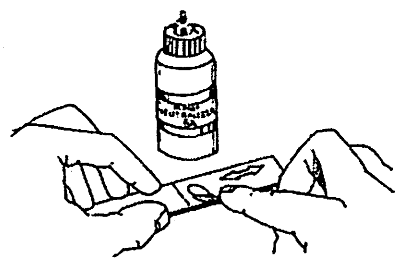


Figure 3

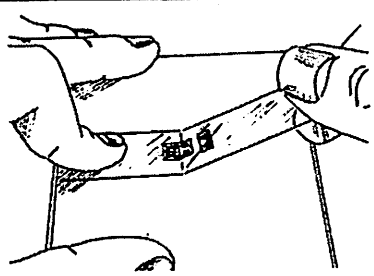


Figure 4

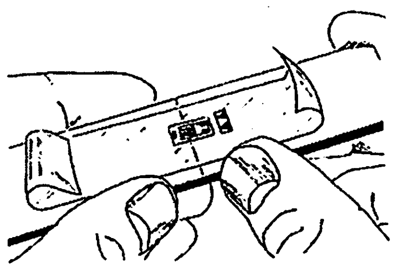


Figure 5

Strain Gage Installations with M-Bond 200 Adhesive

Step 6
Lift the gage end of the tape assembly at a shallow angle to the specimen surface (about 45 degrees) until the gage and terminal are free of the specimen surface (Figure 6a). Continue lifting the tape until it is free from the specimen approximately 1/2 in [10 mm] beyond the terminal. Tuck the loose end of the tape under and press to the specimen surface (Figure 6b) so that the gage and terminal lie flat, with the bonding surface exposed.

Note: Micro-Measurements gages have been treated for optimum bonding conditions and require no pre-cleaning before use unless contaminated during handling. If contaminated, the back of any gage can be cleaned with a cotton-tipped applicator slightly moistened with M-Prep Neutralizer 5A.

Step 7
M-Bond 200 catalyst can now be applied to the bonding surface of the gage and terminal. M-Bond 200 adhesive will harden without the catalyst, but less quickly and reliably. Very little catalyst is needed, and it should be applied in a thin, uniform coat. Lift the brush-cap out of the catalyst bottle and wipe the brush approximately 10 strokes against the lip of the bottle to wring out most of the catalyst. Set the brush down on the gage and swab the gage backing (Figure 7). Do not stroke the brush in a painting style, but slide the brush over the entire gage surface and then the terminal. Move the brush to the adjacent tape area prior to lifting from the surface. Allow the catalyst to dry at least one minute under normal ambient conditions of +75°F [+24°C] and 30% to 65% relative humidity before proceeding.

Note: The next three steps must be completed in the sequence shown, within 3 to 5 seconds. Read Steps 8, 9, and 10 before proceeding.

Step 8
Lift the tucked-under tape end of the assembly, and, holding in the same position, apply one or two drops of M-Bond 200 adhesive at the fold formed by the junction of the tape and specimen surface (Figure 8). This adhesive application should be approximately 1/2 in [13 mm] outside the actual gage installation area. This will insure that local polymerization that takes place when the adhesive comes in contact with the specimen surface will not cause unevenness in the gage glueline.

Step 9
Immediately rotate the tape to approximately a 30-degree angle so that the gage is bridged over the installation area. While holding the tape slightly taut, slowly and firmly make a single wiping stroke over the gage/tape assembly with a piece of gauze (Figure 9) bringing the gage back down over the alignment marks on the specimen. Use a firm pressure with

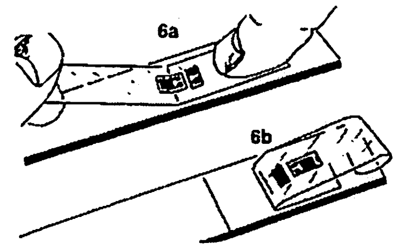


Figure 6

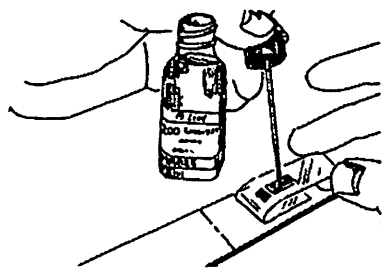


Figure 7

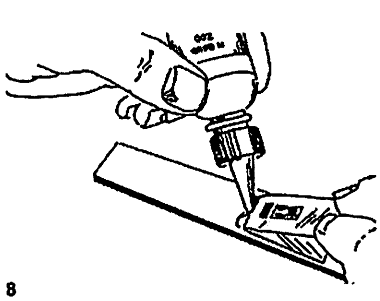


Figure 8

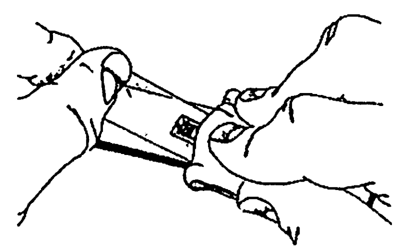


Figure 9

your fingers when wiping over the gage. A very thin, uniform layer of adhesive is desired for optimum bond performance.

Step 10
Immediately upon completion of wipe-out of the adhesive, firm thumb pressure must be applied to the gage and terminal area (Figure 10). This pressure should be held for at least one minute. In low-humidity conditions (below 30%), or if the ambient temperature is below +70°F [+20°C], this pressure application time may have to be extended to several minutes.

Where large gages are involved, or where curved surfaces such as fillets are encountered, it may be advantageous to use preformed pressure padding during the operation. Pressure-application time should again be extended due to the lack of "thumb heat" which helps to speed adhesive polymerization. Wait two minutes before removing tape.

Step 11
The gage and terminal strip are now solidly bonded in place. It is not necessary to remove the tape immediately after gage installation. The tape will offer mechanical protection for the grid surface and may be left in place until it is removed for gage wiring. To remove the tape, pull it back directly over itself, peeling it slowly and steadily off the surface (Figure 11). This technique will prevent possible lifting of the foil on open-faced gages or other damage to the installation.

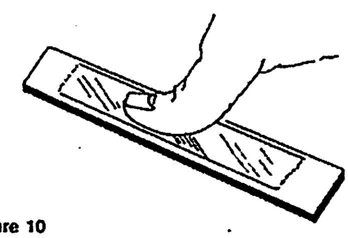


Figure 10

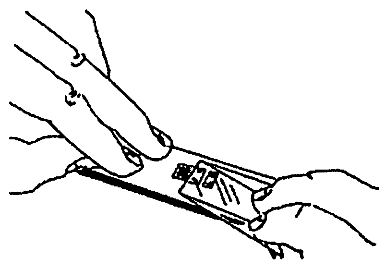


Figure 11

FINAL INSTALLATION PROCEDURE

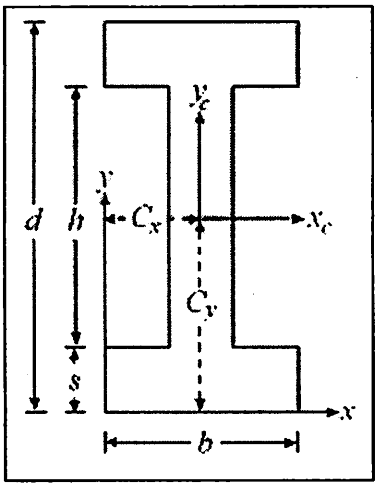
1. Referring to Micro-Measurements Catalog A-110, select appropriate solder and attach leadwires. Prior to any soldering operations, open-faced gage grids should be masked with PDT-1 drafting tape to prevent possible damage.
2. Remove the solder flux with M-LINE Rosin Solvent, RSK-1.
3. Select and apply protective coating according to the protective coating selection chart found in Catalog A-110.

APPENDIX D: CALCULATIONS

Beam Calculations

Max stress is a magnitude lower than the tensile stress of the beam. Therefore beam will be able to take the load.

Moment of Inertia of I-Beam



$b := 5in$

$d := 6in$

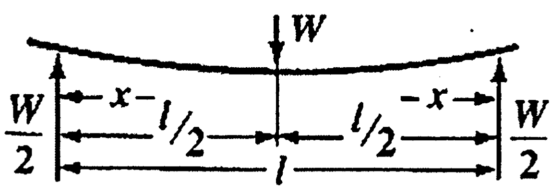
$t := .5in$

$h := 5in$

$$I_{x.c} := \frac{b \cdot d^3 - h^3 \cdot (b - t)}{12} \qquad Z := \frac{I_{x.c}}{\frac{d}{2}}$$

$$I_{x.c} = 43.125in^4 \qquad Z = 14.375in^3$$

Worst Case Senario: Single Point Load



$W := 400lb$

$l := 19.5ft$

$$E_{steel} := 29 \cdot 10^6 \frac{lb}{in^2}$$

$W = 0.2ton$

$$TensilStress_{Steel} := 4 \cdot 10^4 \frac{lb}{in^2}$$

$$\delta_{max} := \frac{W \cdot l^3}{48 \cdot E_{steel} \cdot I_{x.c}}$$

$\delta_{max} = 0.085in$

$$\sigma_{max} := \frac{W \cdot l}{4 \cdot Z} \qquad \sigma_{max} = 1.628 \times 10^3 \frac{lb}{in^2}$$

Bone Preliminary Calculations

Case	Elastic Modulus (Gpa)	Yield Stress (Gpa)	Load (N)	Load (lb)	Max. Stress (Mpa)	Max. Deflection (m)	Max. Deflection (in)
A	4.9	25	13340	2999	24.98	0.076	3.45
B	8.4	63.2	13340	2999	24.98	0.044	2.00
C	8.4	63.2	33360	7500	62.41	0.111	5.05

Determining diameter of a cylindrical representation of the bone.

Approximate cross sectional areas of the bone, based on laser scanned computer model.

2 ft from tip: $A_t := .6ft \cdot .6ft$ $A_t = 0.033m^2$

Middle: $A_m := .4ft \cdot .65ft$ $A_m = 0.024m^2$

2 ft from ball-end: $A_e := 1 \cdot ft \cdot .6ft$ $A_e = 0.056m^2$

$$A_{ave} := \frac{(A_t + A_m + A_e)}{3} \qquad A_{ave} = 0.038m^2$$

$$D_m := 2 \cdot \left(\frac{A_m}{\pi}\right)^{.5} \qquad D_m = 0.175m$$

Elastic Modulus of bone. Values are from a Dugong rib bone (Currey).

Conservative estimates For Modulus of Elasticity and Yield Stress $E_c := 4.9 \cdot 10^9 Pa$ $\sigma_{yield} := 25 \times 10^9 \cdot Pa$

Length of bone $l := 13ft$ $l = 3.962m$

Applied Load $f_n := 3000lb \cdot g$ $f_n = 1.334 \times 10^4 N$

Moment of Inertia $I := \pi \frac{D_m^4}{64}$ $I = 4.643 \times 10^{-5} m^4$

Section Modulus $Z := \pi \cdot \frac{D_m^3}{32}$ $Z = 5.295 \times 10^{-4} m^3$

Determining stresses and deflections for a simply supported beam with a point load in the middle.

Stress $\sigma_{max} := \frac{f_n \cdot l}{4 \cdot Z}$ $\sigma_{max} = 2.497 \times 10^7 Pa$

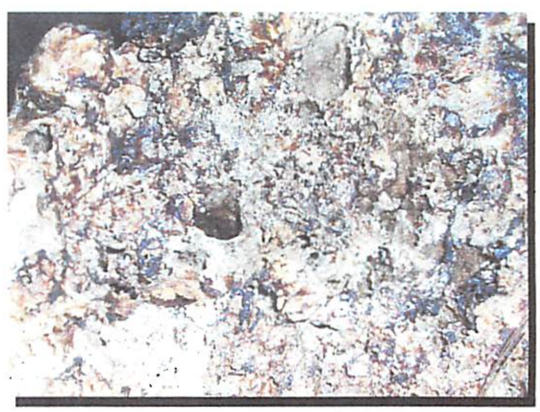
Deflection $\delta_{max} := \frac{f_n \cdot l^3}{48 \cdot E_c \cdot I}$ $\delta_{max} = 0.076m$

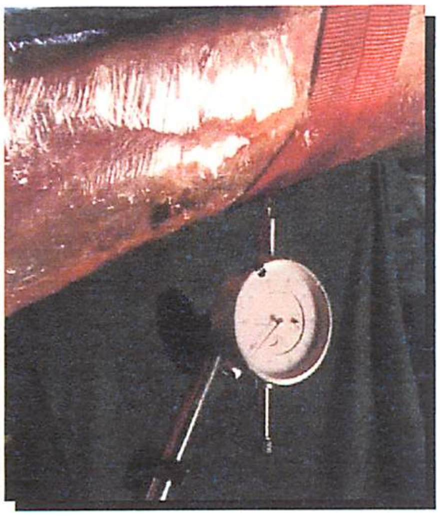
Appendix F: Project Pictures

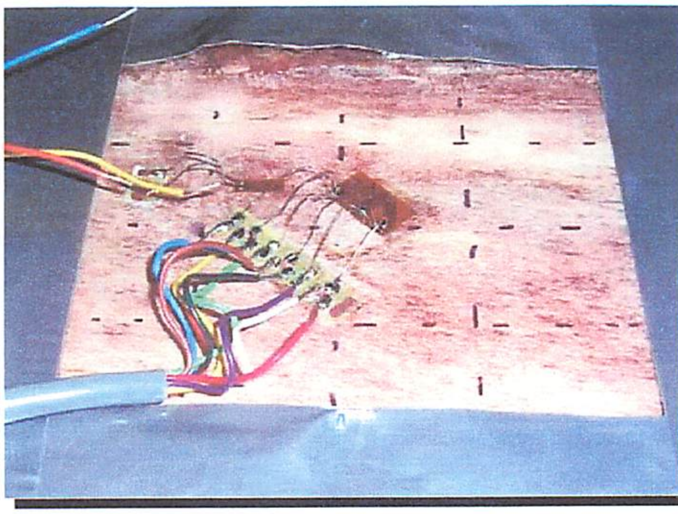
The following pages show pictures taken throughout the course of the project. Some experimental testing setup pictures can be seen, as well as comparisons of the size difference of the minke whale and right whale mandibles. More images are available upon request.

Counterclockwise from top:

Mandibular socket joint of mandible. Outside face of bone. "Chin" end of mandible. Bone texture, as seen from a cross sectional fracture.







Counterclockwise from top:

Strain rosette with additional gage on bone. Dial indicator under bone. Experimental testing setup, shown with 1000 lb load being applied. Cooling container shown with the larger right whale bone behind smaller minke whale bone.