Verifying the Accuracy of BDI Strain Transducers

Often, our customers like to verify the accuracy of their new BDI Strain Transducers, something that we encourage them to do. However, there are several pitfalls that can be made while trying to check these sensors out in the laboratory. Having fielded similar questions from several customers, we have assembled the following explanations to help avoid some of these problems. In almost all of the cases we have seen, the measurements have been proven to be correct, and the assumptions made in the "strain application system" or structural system are either incomplete or incorrect.

Remember that these accurate sensors have been designed to help obtain the structure's overall behavior, rather than at possible stress concentrations like at connections and rivet points. This is because most bridge ratings are controlled by the flexural or shear stresses, rather than localized stresses at a connection. Therefore, it is best to keep the transducers away from stress concentrations or structural non-uniformities. For measuring local strains in tight areas, either a small foil strain gage or an alternative method such as photoelasticity is required.

Background:

These full-wheatstone bridge strain transducers were originally developed in about 1970 for use in the driven pile industry. They were designed for recording strains on the side of a pile (steel or concrete) as it was being driven with a pile hammer. This operation applies very high accelerations and requires a very rugged sensor to survive. Over the ensuing years, the transducers have been tested extensively to determine their limitations, often leading to design refinements. Based on the latest design, the BDI Strain Transducers have been modified slightly through the use of a different type of internal strain gage that is better suited for static or "semi-static" structural load testing.

Factory Calibrations:

These sensors are calibrated by inputting a known excitation voltage and applying a known strain and then recording the output over approximately a 1000 $\mu\varepsilon$ range. The manufacturer's calibration that we supply is performed with a NIST-traceable system that consists of a small precision slide table and an optical displacement sensor. The entire calibration process is always verified by a calibrated precision micrometer. Reproducibility of this system is typically better than one percent and in no case worse than two percent.

In field test applications with linear-elastic structures, we have found repeatedly that we can expect reproducibility of the measurements of approximately ± two microstrain. The errors contained in this result included differences in load (truck) placement. Thus, one can expect that every field test can have an error of two microstrain. This, of course, is insignificant for quantifying the behavior of a large civil structure.

Temperature Effects:

The BDI Strain Transducers have been designed for recording LIVE LOAD strains only. Hence it is assumed that there will be little to no temperature change during any short time-span testing sequence. For example, most highway bridge tests (a truck passage at crawl speed) can be completed in less than one minute, usually not enough time for ambient air temperatures to change significantly. If the sensor is to be mounted on the structure for a long period of time, it will need to have its "zero" reset periodically as it drifts around with temperature changes. The primary reason that these sensors drift with temperature (even a steel transducer on a steel structural member) is due to large difference in thermal inertias. Because of the relatively small mass of the transducer compared to a typical structural member, the rate of temperature change and therefore thermal expansion of the transducer is much greater. When a transducer is attached to a structure, it is forced to have the same deformation as the structure. However, if a temperature increase (or decrease) occurs, and since the ends of the sensor are "anchored", the transducer will expand between the end blocks and register compression. The same goes for a drop in temperature which will register tension. It is very difficult to separate the temperature effects on the gage from the actual temperature-induced strains, particularly on statically indeterminate structures.

If the transducers are exposed to direct sunlight during live-load tests, such as on truss members or on top of a concrete slab, significant temperature drift can be experienced during short periods of time due to changing cloud cover. Covering the gages with rags or packing material can usually reduce or eliminate this problem.

Specimen Type and Size

Often, the first verification test to be performed is either on a bending beam or compression/tension specimen in some kind of laboratory testing machine, with the results compared to the output of a foil strain gage or the theoretical strain value. Some of the items to consider during such tests are listed below:

1) Remember that these sensors are designed to measure "axial strain". Flexural bending on structural members can be determined via axial strain measurements as long as the applied curvature is relatively small such that the small angle theory is applicable (SIN $\theta = \theta$). This means that if bending stresses are to be measured, it is best to use a beam with a minimum depth of approximately 12" or more, since the transducer will actually be offset from the beam surface slightly due to the thickness of the mounting tabs. However, with the beam depth of 12" or more, this difference is minimal. Another thing to watch out for during a beam bending test is that it is very difficult to apply the load to the beam without inducing some kind of torsion or lateral bending. This occurs because the beam was not perfectly "straight" or because the end conditions are not perfectly level with one another. To minimize this, the transducers should be mounted with the tab/adhesive technique to the center of the flanges, rather than with C-Clamps on the edge of the flanges.

Trying to measure the strain on a 2" wide strip of metal that is 1/8" thick and mounted as a cantilever beam is not a good verification test for these sensors. The primary problem with a thin bending specimen is that a large degree of curvature is required to obtain a small level of surface strain. In other the words, the transducer will simply be bent rather than elongated. Furthermore, the actual location of the transducer will be relatively far from the neutral axis compared to the surface (aggravated again by the thickness of the tabs if they are used). Therefore, significant errors are induced when comparing surface strains obtained by a foil strain gage and the transducer reading.

For calibration purposes, it is highly recommended that strains be compared at constant moment regions rather then at locations with significant moment gradients. For the "bending beam" type of test, we recommend a beam at least 10 ft to 12 long, with a shorter beam (4 ft to 6 ft) set on top (with "pins" under each end), and the load cell above that. This "4-point" type of setup will supply a constant moment region at midspan. Remember, the strain measured from the transducers are averaged over the 3" gage length. Therefore any error in gage placement or in the assumed strain gradient will cause errors in subsequent data comparisons.

2) In almost every case we have seen, a specimen that is supposedly undergoing tension only is actually bending as well. A popular test is to use a "dog bone" with the transducer mounted on one side and then the whole assembly put into tension. It is almost impossible to get pure tension in this setup since the specimen may be slightly bent to begin with and "straightens out" slightly. Also, since the transducers themselves have a small amount of stiffness, they will cause a non-symmetrical system. Another consideration is the distance of the centroid of the transducer to the specimen's neutral axis. Since bending will most likely occur, the output from the transducer may be reduced or amplified since its centroid is about 1/4" away from the foil gage (further from the neutral axis), and this might be the "compression" or "tension" side of the specimen. This phenomenon is very critical on small laboratory specimens, but insignificant on larger structures where the depths of the sections are usually much bigger.

In order for the tension test to be successful, transducers should be mounted on both sides of the specimen (on all four sides if the stiffnesses are similar in two directions) and the output averaged to determine the tension strain. In addition, the specimen should be relatively stiff compared to the transducer.

3) If a compression test is being attempted, then the gages need to be at least two member depths away from the ends (a criteria for plane strain) and gages mounted on both sides of the specimen and the data averaged. For compression specimens, it may be necessary to place gages on all four sides since it can often be difficult to know the exact orientation of the neutral axis if the stiffness is approximately the same in both directions.

4) Using reinforced concrete as a test specimen material is a poor choice since inaccuracies in the reinforcement locations and variations in the concrete's elastic modulus (often up to 20%) can cause larger errors than the accuracy range of the strain transducers. For example, more aggregate near the surface of one gage will affect the modulus in that area. The way BDI addresses strain measurements on reinforced concrete is to use gage extensions, effectively amplifying the strain over anywhere from two to eight gage lengths, then taking an average. We accept the idea that concrete strains are not as accurate as those taken on steel structures, and attempt to maximize the accuracy with the gage extensions. This approach amplifies the signal, thus also improving the signal to noise ratio. With a gage length that is too short, stress concentrations, microcracking, or local effects might have an unusually large effect on the measurements.

For reinforced concrete structures (non prestressed or post tensioned), because of the margins of unknowns in concrete modulus, load magnitudes, placement of reinforcement, etc., in general, we prefer not to use measurements where the maximum strain is less than about 30 microstrain if we are making conclusions based on the magnitude of strain. (Note that 2 $\mu\varepsilon$ is almost 10% of a 30$\mu\varepsilon$ peak). This translates into only about 100 psi in concrete and 1 ksi in steel, which is really quite accurate for analytical modeling and load rating reinforced concrete structures. For these types of structures, numbers that are claimed to be more accurate are probably suspect. Using the transducers on prestressed concrete will usually provide excellent measurements, not only because there shouldn't be any cracking, but the concrete modulus usually tends to be more uniform.

5) Under no circumstances should loads be applied directly to the strain transducer. The transducers are designed with a very flexible geometry. This enables large strains to be measured with little axial load being transmitted through the transducer. Therefore, when testing typical structural members, the stiffness of the transducer is inconsequential. The transducer is intended to provide a measure of strain; it is not a load cell.

Other Considerations:

Excitation Voltages and Electronics: BDI recommends that the Wheatstone bridge excitation voltage stay at or below 10VDC for these sensors. Higher voltage levels can cause drifting and stability problems in the 350Ω foil gages in the transducers. The BDI Structural Testing System uses 5VDC with very good results. A good discussion on this topic is provided in Tech Note 502 entitled "Optimizing Strain Gage Excitation Levels" available from MicroMeasurements. It is also best to use a high-impedance measuring device, something that most data acquisition systems offer. If extension cables are added, remember that these can add a slight amount of offset and possibly some signal attenuation. Allowing the electronics and the gages to warm up for several minutes is also recommended. A small amount of drift will be detected as the gages warm up, but should stabilize in under several minutes.

Measuring the Applied Strain or Load: Often, the output of a strain gage-based load cell is used in a testing machine as the basis for comparisons in tension/compression tests. However, we have found that many of these units may not have been NIST-calibrated for years and may be producing inaccurate results. If a gage is manually read for hydraulic pressure, then the result will be sensitive to jack friction. Also, if stress and strain are being calculated ($\sigma = E\varepsilon$, $\sigma = My/I$, etc.), then accurate measurements of the cross-sectional areas are required.

Magnitude of Applied Loads: Calibration tests should always be run up near the maximum safe linear range of the system. This will give the required confidence that the outputs from the transducers are indeed linear over the range of stresses of interest.

Recording Data: It is VERY important to record the data continuously, rather than discreetly. A qualitative review of the strain history will often be even more important than the actual magnitude because possible electronic noise or other effects will immediately be apparent. Furthermore, the other sensors such as load cells and foil strain gages should all be recorded with the same equipment and at the same sample frequency as the transducer data. This again allows for a qualitative check to be completed.

We are confident that if the above precautions are taken, the BDI Strain Transducers will provide very accurate and reproducible results. If you have any questions on the above discussion or have a lab testing "pitfall" experience that you would like to have us investigate or think it may help other users, please contact us.