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How they work

LOAD / FORCE CELLS



The load or force cell takes many forms to accommodate the variety of uses throughout research and industrial applications. The majority of today's designs use strain gauges as the sensing element, whether foil or semiconductor.

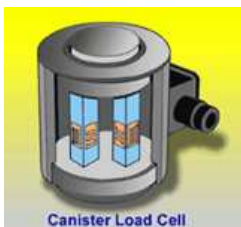
Foil gauges offer the largest choice of different types and in consequence tend to be the most used in load cell designs. Strain gauge patterns offer measurement of tension, compression and shear forces.

Semiconductor strain gauges come in a smaller range of patterns but offer the advantages of being extremely small and have large gauge factors, resulting in much larger outputs for the same given stress. Due to these properties, they tend to be used for the miniature load cell designs.

Proving rings are used for load measurement, using a calibrated metal ring, the movement of which is measured with a precision displacement transducer.

A vast number of load cell types have developed over the years, the first designs simply using a strain gauge to measure the direct stress which is introduced into a metal element when it is subjected to a tensile or compressive force. A bending beam type design uses strain gauges to monitor the stress in the sensing element when subjected to a bending force.

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Canister Load Cell

More recently the measurement of shear stress has been adopted as a more efficient method of load determination as it is less dependent on the way and direction in which the force is applied to the load cell.

The 'S' or 'Z' Beam Load Cell

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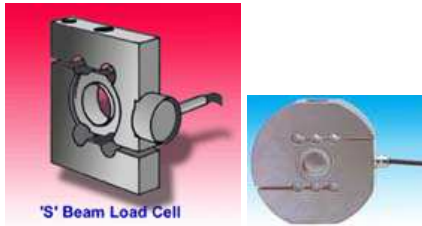
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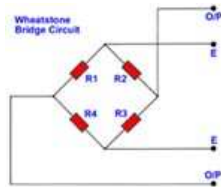
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A simple design load cell where the structure is shaped as a 'S' or 'Z' and strain gauges are bonded to the central sensing area in the form of a full Wheatstone bridge.

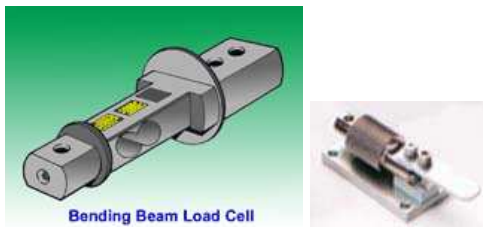
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The Wheatstone Bridge Circuit



E = Excitation Voltage (typically 10 Vdc.)
O/P = Output Signal

The Bending Beam Load Cell



The strain gauges are bonded on the flat upper and lower sections of the load cell at points of maximum strain. This load cell type is used for low capacities and performs with good linearity. Its disadvantage is that it must be loaded correctly to obtain constant results.

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The Shear Beam Load Cell



The strain gauges are bonded to a reduced part of the cross section of the beam in order to maximise the shear effect. They are bonded at 45 degree angles on either side of the beam to measure the shear strains.

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Used for medium to large capacities, the load cell has good linearity and is not so susceptible to extraneous loading, in particular to side loads.



Miniature Load Cells



Miniature load cells because of their compact size usually use semiconductor strain gauges as the sensing element. They are available in many different configurations for both tension and compression force measurement. They offer good performance with high outputs and high overload capability for protection.

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Speciality Automotive/Autosport Load Cells



Many more Load Cell designs exist and we will bring you details of these at a later stage.

LOAD CELL SPRING MEMBER DESIGN CONSIDERATIONS

Bending: Simple

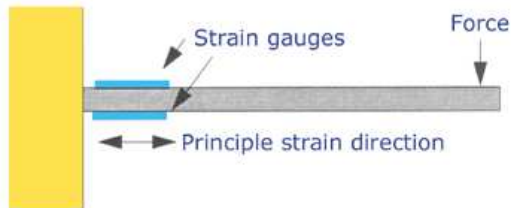


FIGURE 1. Bending: The simple cantilever

Bending elements are low-force, generally less than 1,000 lbf range, high-deflection structures offering convenient and flat strain gauging surfaces where complete push/pull strain symmetry is maintained.

Two strain gauges may be mounted on the top surface of the beam with two strain gauges mounted on the bottom of the beam in equal and opposite strain fields. Since strain gauges are directly opposite one another and beam thickness tends to be small, little likelihood exists that the strain gauges will operate at different temperatures providing generally good thermal performance. Although the cantilever beam structure provides excellent electrical nonlinearity, due to electrical symmetry, the point of load contact with the beam translates curvilinearly, producing mechanical nonlinearities.

The maximum moment resisting movement of the beam occurs at the rigid clamp with the maximum stress occurring according to $M/y/E$ where M = moment at the clamp, y = displacement from the centerline of the beam (neutral axis), I = area moment of Inertia and E = Young's Modulus for the material used. Since the majority of the beam length serves only to increase the moment at the rigid clamp, various modifications of the simple beam are used to reduce the beam mass in the interest of maintaining a high natural frequency or to concentrate the strain at the strain gauge locations as shown in Figure 2.



Lastly, a review of beam bending characteristics of reveals that the surface strain present in the beam surface linearly varies from the point of force application to the clamp. This implies that the strain gauges will experience a strain gradient and provide an output equating to the average strain. Constant stress beam sections can be fabricated by tapering the edges of the beam such that the tapered edges projected intersect at the point of load application to the beam as shown in top view Figure 2. In the end analysis, the load cell designer must weigh the performance benefits produced against the cost of incorporating the mechanical features shown.

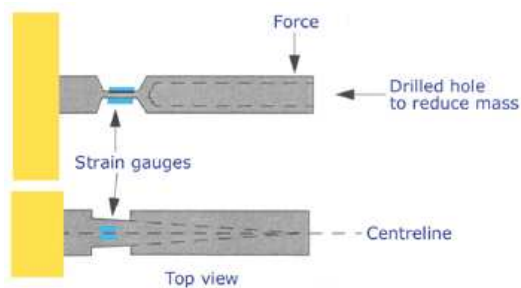


FIGURE 2. Simple Cantilever Enhancements

Bending: Multiple

Multiple cantilever structures produce a "multiple bending" where tension and compression strain fields exist on the same surface of the beam as shown in Figure 3a. The advantage of multiple bending elements is realized when one considers that the point of load application to the structure translates linearly along the loading axis, thereby reducing or eliminating first order nonlinearities. When the

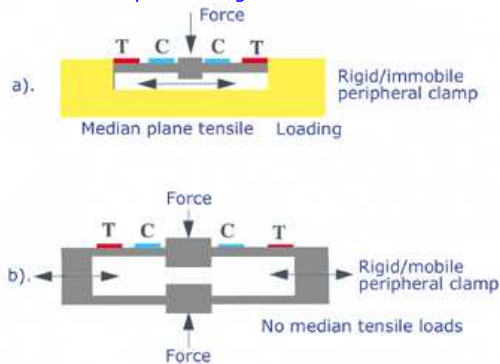
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how sensors work - load cells

peripheral support clamp is rigid and immobile, deflection of the bending beams also produces median plane tensile loads in the beam resulting in nonlinear outputs. When the peripheral clamp is rigid and mobile, as shown in Figure 1, median plane tensile stresses are eliminated however, as the beams deflect, the moment arm reduces in length yielding yet another non-linear term and doubling the deflection of the load cell. Note that "T" is used in the Figure to denote tensile strains and "C" is used to denote compressive strain.

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FIGURE 3. Multiple Bending:



Multiple bending can be implemented as shown in Figure 4 where the sensitivity of the load cell to off-axis loads is minimized. Coupled dual-beam load cell configurations conveniently produce equal and opposite axial loads within each of the beams in response to extraneous couples. Since the strain gauges can be wired to cancel the effects of axial loads, the result is a load cell structure largely insensitive to the point of load application and particularly well-suited to commercial weighing applications. As the beams deflect, however, small changes in the moment arm lengths result producing geometric nonlinearities.

Additionally, axial forces produce nonlinearities in each beam which tend to be equal and opposing, thus canceling each other.

Although

strain gauging inside a drilled hole is more labor intensive, the design

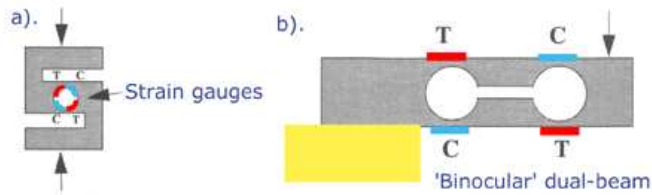
lends itself to effective sealing. Often vacuum degassed silicone gel materials are used to fill the interior strain gaged cavity waterproofing by the "exclusion" principle.

The "binocular" dual beam design of Figure 4b is popular for low force commercial weighing applications. The thickened sections resist bending thereby reducing the compliance of the design and maximizing the natural frequency. Note that the maximum strain occurs at the transduction zones and is less than this value everywhere else within the structure. Low-profile bending-based load cells are usually configured as strain gaged diaphragms or multiple strain-gaged spoke assemblies.

Often, low profile multiple-bending designs possess four spokes at 90 degree intervals where strain gauges are wired to cancel off-axis moment-induced strains. It should be noted; when in the process of designing any load cell structure, the designer must consider all bending as well as shear loads that the spring element must communicate.

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FIGURE 4. Coupled Dual-Beam Cantilevers:



Many of the designs shown are depicted herein possessing right-angled corners. To minimize stress concentrations that will occur at geometric discontinuities, it is highly recommended that generous fillets be used with particular attention to possible discontinuities at surfaces tangent to radiused features. Stress risers will often show local stresses in excess of the microyield strength of the material used, producing zero instabilities and potential fatigue failures.

Forty years ago sensor designers found that performance was almost always enhanced when the sensor was fabricated from a solid billet of material and attention paid to the elimination of structural discontinuities. Today we have a much more refined understanding of materials and material behavior along with the terminology to express these various attributes and characteristics.

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Bending: Ring

The bending ring shown in Figure 5 has a rich history and is popularly known as the Morehouse proving ring. The original design having been appropriated from Russia. The Morehouse proving ring was and continues to be used as a transfer standard in both sensor calibration systems and materials test systems. It is obvious from the design of the ring that each leg of the ring must communicate axial loads while simultaneously experiencing bending. The fact that both axial and bending occur within the transduction zone of the sensor characterizes ring-style load cells.

The beauty of the proving ring with strain gauges installed as shown is the fact that all gauges of the wheatstone bridge ideally experience identical axial strain, resulting in cancellation of axial strain effects in the output of the bridge. Another attribute of the ring structure relates to the smoothly varying tensile and compressive moment-induced strains that result due to loading of the cell. The original transduction method used with the structural ring design predates strain gauges entirely where a manually "plucked" metal reed and micrometer assembly were used to detect exceptionally small deflections of the ring. A hardened ball bearing acts as the micrometer-adjustable target surface against which the reed tip oscillates, where the reed is also provided with a hardened cylindrical tip, the micrometer is adjusted to move the target until the reed just contacts the target, dampening the reed response. The displacement sensitivity of this very mechanical system is impressive. The output of the sensor is viewed directly on the micrometer scale.

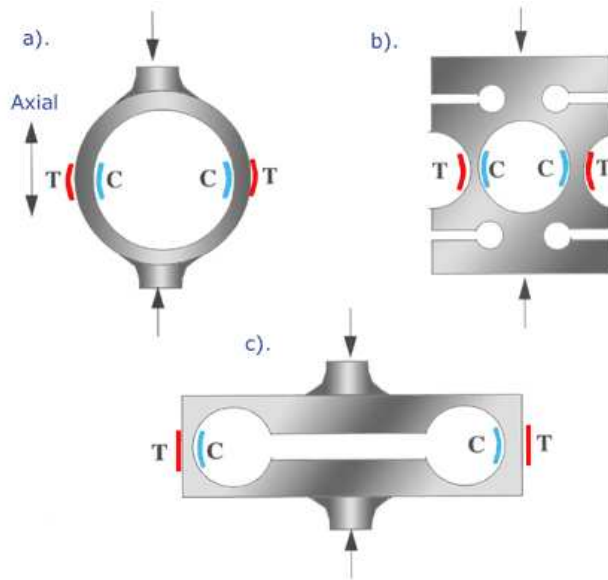
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It should be noted that the design of the bosses communicating load into the ring structure significantly affects the performance of the ring. The optimum proportions and dimensions of these bosses is as much determined by experience and test as it is by rigorous mechanical design.

Bosses are often undercut or modified to be made more flexible in the interest of rejecting off-axis loads trading off performance for off-axis load rejection. Likewise, transduction zones are provided with stress- concentrating notches to enhance output, natural frequency and to reduce compliance. In some cases, the extent to which these boss and flexure modifications extend are so radical as to almost defy characterization as a ring-based load cell. The

single common thread in all of these designs is the fact that transduction zones must communicate both bending and axial loads.

FIGURE 5. Bending: The ring:



Shear:

Strain gauge-based load cell structures, configured to operate based upon the measurement of shear strain, provide high capacity and low compliance in a compact and low profile geometry. Strain gauges measuring shear are oriented at 45 degrees to the neutral axis in bending and are mounted to straddle the neutral axis. Bending stresses are, by definition, equal to zero at the neutral axis in bending. Although the strain gauge must possess some finite physical dimensions, by equally straddling the neutral axis in bending, half of each strain gauge will experience some bending strain while the other half will experience the same strain in the opposite direction thereby largely cancelling bending in the output of the sensor. Practically, the shear patterns cannot be positioned with absolute perfection and shear webs cannot be fabricated with absolute symmetry resulting in less than perfect cancellation of bending strains.



Unlike bending stresses developed in the cantilever beam structure, where bending stresses are a direct function of moment which itself

is a direct function of the moment arm, shear stresses by definition are equal only to the load carried by the member and the area of the member, independent of the point of loading. By varying the thickness of the load-bearing member, the shear stresses are varied in direct proportion. Utilizing this philosophy, load carrying beams are often milled out to create shear "webs" possessing an area sufficient to produce shear strains in the 1,000 to 1,700 microstrain range thereby yielding strain gauge full-bridge outputs of between 2 mV/V and 3 mV/V.

Shear strain gauge patterns are often used to strain gauge dual-axis

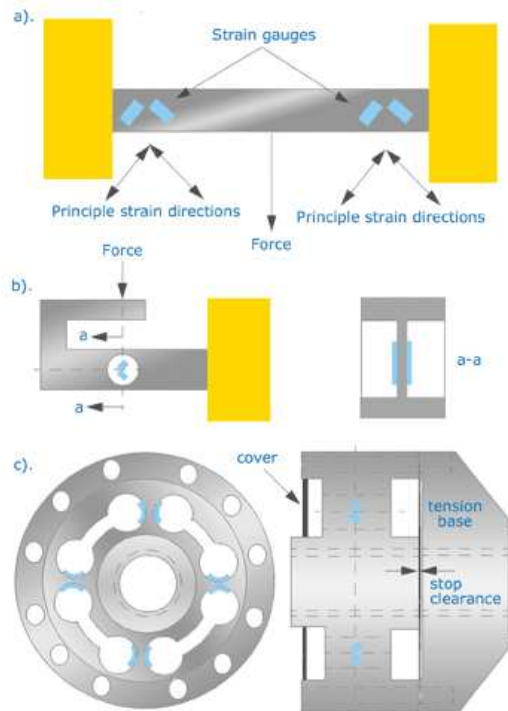
shear pin structures by gauging the inside diameter of a hole drilled in a cylindrical member. The diameter of the internal hole is dimensioned to result in a shear area sufficient to produce the desired strains at rated input. The central hole is readily sealed, usually by welding of a hermetically sealed connector, rendering

the design useful in hostile environments.

In physically realizable sensor structures, it is impossible to configure the structure to experience pure shear without the presence of some bending. The load bearing members must therefore communicate both forms of material loading. Due to higher-order effects tending to couple shear and bending strains, and in the interest of minimum compliance, it is advisable to configure the spring member for minimum bending. The reduction of spring member length will have the effect of reducing moments and bending strains. The geometry induces double bending where the inflection point is centered on the shear web thereby minimizing the bending that results at the strain gauge locations.

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Figure 6. Shear:



The popular "pancake" style load cell, as shown in Figure 6c, is configured to operate in shear, offering a very low profile in a design that is easily environmentally sealed and is largely insensitive to off-axis loads. Generally, pancake style shear web load cells are available in the 1,000 lbf and higher load ranges.

The pancake style load cell also easily accommodates dual electrically -separate strain bridges for high reliability applications. The high stiffness "tension"-base serves to allow the measurement of tensile forces, acts to stiffen the load cell structure in compression and to allow the incorporation of overrange limiting stops for compression applications. Low profile pancake load cells are not available in the under 500 lbf force range since the shear web thickness becomes exceedingly thin and difficult to manufacture. It should be noted that the strain gage clamping fixtures for the pancake style sensor either pinch the shear webs to avoid overstressing them during manufacturing or all cylindrical gaging holes shown are filled with teflon plugs which provide clamping pressure due to volumetric expansion at elevated epoxy cure temperatures. The teflon plugs used are closely-toleranced to the diameter of the gauging holes and tend to extrude into the hole-to-hole slots reducing the clamping pressure

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as a function of the number of cure cycles they have been exposed to.



The design section of this article was written by Mr. James Pierson

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