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Abstract. This article gives a detailed description of the development of an experimental sensor beam support with an integrated load cell, in this paper also named a smart support. The smart support is designed as a part of a beam bending experimental apparatus. For small universities, the financial effort needed to equip experimental mechanics labs is considered unjustified for the purpose of undergraduate mechanics classes. Thus the majority of experiments conducted in mechanics and similar classes are done during lectures as 5-minute presentations using available, inexpensive and simple apparatus. Such apparatus was produced in faculty workshops, by students as a part of undergraduate theses or projects with sponsoring companies. This article describes a process of building experiment apparatus through the student undergraduate theses and cooperation with local companies. It also shows the current state of beam bending apparatus at University North and the process of creating the initial design of a smart support. Some properties of two typical versions of load cells containing strain gauges were investigated using numerical simulations. According to load cell shapes, two different design solutions of smart support were proposed. The final chapter describes future plans to create data acquisition and ideas for developing further experimental modules or devices for various other experiments.

1. Introduction

Equipping a mechanics lab represents a large expense, especially for the small universities and in the view of the traditional vector mechanics classes somewhat unjustified considering a large financial effort, a short effective time and a limited usage of the experimental apparatus. Majority of mechanics classes are theoretical while experiments are not considered as beneficial as solving example problems. Such opinion prevails partially because simple experiments were already shown in primary and secondary school physics and more sophisticated experiments are not used due to numerous reasons. Besides the financial obstacles, a course structure, strictly defined learning outcomes, large groups of students attending classes, insufficient classrooms and overloaded lecturers do not allow spending time on such tasks as conducting experiments. Another reason is that doing more complicated measurements demands foreknowledge in subjects in which students do not get insight until they start senior classes. Experiments in Mechanics classes at undergraduate engineering level are rare and fruit of an individual lecturer's ideas and efforts.
2. Supports

Structural systems transmit the load through the connections to the rest of construction, or to the ground. Each connection is designed to transfer a specific type of load or loading condition. These connections we often call supports. According to reactions exerted on a structure, in case of two-dimensional structures, we divide supports or connections into three groups:

- supports and connections causing reactions equivalent to a force with a known line of action,
- supports and connections causing reactions equivalent to a force of unknown direction and magnitude and
- fixed supports causing reactions equivalent to a force and a couple.

Most common types of supports for two-dimensional structures, their reaction forces and a number of unknowns are listed in Table 1.

| Support or connection | Reaction | Unknowns |
|-----------------------|----------|----------|
| Rollers               | Force with a known line of action | 1 |
| Frictionless surface  | Force of unknown direction | 2 |
| Frictionless pin or hinge | Force and couple | 3 |

This work investigates a simplified case of a freely supported beam on a frictionless surface. Two design solutions of the smart support with integrated load cell were developed according to this simplification.

While in this work the impact of friction was ignored, in the future research projects will consider effects of friction on a rough surface, fixed supports and resulting deflection curve. As effects of friction and additional moment in a fixed support and resulting deformation of a beam are limited, research will depend on the precision of measuring devices or availability of precise measuring equipment. Finite element analysis of assorted design solutions would be an effective tool for predicting a complicated actual behaviour of supports.
3. Beam bending apparatus

Devices for conducting physical experiments were designed and even available for purchase for centuries. A historical example is an apparatus for a static experiment of measuring reaction forces, as shown in Figure 1. Based on a purely mechanical principle of counterbalancing concentrated force acting on a beam, weights were connected to a beam by rod and pulley to balance the acting force. Depending on the load, weights were added on both ends to balance the beam.

![Figure 1. Apparatus for measuring reaction forces [1].](image)

The second example of structural experiment apparatus is in Figure 2. It is a more recent example, and it shows a mechanical device for measuring module of elasticity or beam deflection. This apparatus has two tripod holders acting as fixed supports while it uses a dial gauge to measure deflection at the middle of the beam. Dial gauge can also be used to determine the characteristic bending curve of a beam. The measured deflection, beam cross-section area moment of inertia, and the distance between supports can be used to calculate other mechanical properties, e.g. modulus of elasticity.

![Figure 2. Apparatus for determining the modulus of elasticity [2].](image)  ![Figure 3. Beam bending frame student project [4].](image)

Finally, beam-bending frame inspired by structures test frame designed by Tecquipment [3] is in Figure 3. The experimental frame design enables using interchangeable experiment modules. At the time of submitting this paper, only beam bending experiment module is available for experiments.

The experimental frame was designed as a student undergraduate thesis project and manufactured by the student's employer. It was donated to University North and currently situated at university laboratory for measurements. This frame is one of the experimental mechanic equipment units that university has. The second unit is rotor dynamics demonstration device, designed by two students and
manufactured by their employer.

On the experimental frame in Figure 4, the beam is freely supported at two points with the load applied in the form of concentrated force. Forces were applied as weights of known mass. The frame in the current state has dial gauge for measuring beam deflection while dynamometer can be used to measure reaction forces.

This work proposes replacing passive supports with smart supports. Two smart supports or supports with integrated load cells were developed based on two different designs of a load cell.

4. Load cells
For the purpose of this research strain gauge load cells were used. The strain gauge load cell is the most common type of force transducer. Each cell is based on an elastic element to which a number of electrical resistance strain gauges are bonded. The geometric shape and modulus of elasticity of the elements determine the magnitude of the strain field produced by the action of the force.

Each strain gauge responds to the local strain at its location, and the measurement of force is determined by a combination of these individual measurements of strain. The rated capacities of strain gauge load cells typically range from 5 N to more than 50 MN and they have become the most widespread of all force measurement transducers [5].

Figure 5 shows typical elastic elements and their usual rated capacities [5]: a) compression cylinder 50 kN to 50 MN, b) compression cylinder (hollow) 10 kN to 50 MN, c) toroidal ring 1 kN to 5 MN, d) ring 1 kN to 1 MN, e) S-beam (bending or shear) 50 N to 50 kN, f) double-ended shear beam 20 kN to 2 MN, g) double-bending beam (simplified) 500 N to 50 kN, h) shear beam 1 kN to 500 kN, i) double-bending beam 5 N to 10 kN and j) tension cylinder 50 kN to 50 MN.

5. A smart support design
In this research project, two basic designs of load cells were used: a double bending beam and an S-beam (Figure 5. parts i and e) and accordingly two designs of a smart beam support were proposed. In the first solution for the simple support double bending beam was used. The double bending beam, in such design solution, can only be used to measure compression force.

When force is applied elastic element will deform and strain gauges will show a change in electrical resistance at the output electrical signal. The change in resistance may be measured and used to calculate the force from the calibration of the device.

The second proposed design solution is done using S-beam load cell. This solution was expected to give a better accuracy of measurement due to the shorter element and more direct force transmission.

The hinge was also designed with integrated S-beam load cell and can be used to measure compression and tension force.
Figure 6. Simple support with double bending beam load cell [7].

Figure 7. Simple support with S-beam load cell [7].

Figure 8. Hinge with S-beam load cell [7].
6. A beam support simulation

Some simulations using finite element analysis (FEA) were done to predict smart beam support behaviour in working conditions under the applied load.

Strain values for the gauge middle line were extracted. Those strain values are results of the compression or extension of the elastic element fiber due to the bending of the element. The bending of the gauge has a similar effect, however, the compression and extension of the upper and lower fibers are of similar intensity and the opposite direction so that they are mutually annulled and do not affect the change of resistance. Therefore, the change of resistance is affected by the extension of the gauge in the \( x \)-direction, and its compression \( y \) and \( z \) directions, which can be calculated by taking into account the value of the Poisson coefficient.

![Figure 9. S-beam FEM model [7].](image)

The first simulation was performed in 10 steps applying loads ranging 0-100 N, while 100 N was maximum load for simple lab use. The extension values of each middle line element were processed in Excel, after which an average of the relative extension of individual elements was calculated for each step. Since the size of the elements is the same, the total extension of each strip can be obtained by multiplying the mean value of extension of the gauge and its initial length. Results of this numerical experiment are shown in Table 2.

| Load force [N] | Mean value of strain [\( \mu m/m \)] | Elongation [\( \mu m \)] |
|---------------|-------------------------------------|-------------------------|
|               | Gauge 1    | Gauge 2    | Gauge 3    | Gauge 4    | Gauge 1    | Gauge 2    | Gauge 3    | Gauge 4 |
| 10            | -25.0      | 27.7       | -24.8      | 27.5       | -0.12      | 0.14       | -0.12      | 0.14    |
| 20            | -50.0      | 55.3       | -49.7      | 54.9       | -0.25      | 0.28       | -0.25      | 0.27    |
| 30            | -74.9      | 83.0       | -74.5      | 82.4       | -0.37      | 0.41       | -0.37      | 0.41    |
| 40            | -99.9      | 110.6      | -99.3      | 109.9      | -0.50      | 0.55       | -0.50      | 0.55    |
| 50            | -124.9     | 138.3      | -124.2     | 137.4      | -0.62      | 0.69       | -0.62      | 0.69    |
| 60            | -149.9     | 165.9      | -149.0     | 164.8      | -0.75      | 0.83       | -0.74      | 0.82    |
| 70            | -174.8     | 193.6      | -173.8     | 192.3      | -0.87      | 0.97       | -0.87      | 0.96    |
| 80            | -199.8     | 221.2      | -198.7     | 219.8      | -1.00      | 1.11       | -0.99      | 1.10    |
| 90            | -224.8     | 248.9      | -223.5     | 247.3      | -1.12      | 1.24       | -1.12      | 1.24    |
| 100           | -249.8     | 276.5      | -248.3     | 274.7      | -1.25      | 1.38       | -1.24      | 1.37    |
Change of length of each individual gauge depending to load force has a linear trend. Tension and compression strain of corresponding gauges are matching and their deviation can be limited using Wheatstone bridge.

![Diagram of Wheatstone bridge configurations](image)

**Figure 10.** Full bridge configurations [8].

![Diagram of full bridge configurations](image)

**Figure 11.** Simplified full bridge equations [9].

A full-bridge strain gage configuration has four active strain gages and is available in three different types: configuration I (Figure 10.a), configuration II (Figure 10.b), configuration III (Figure 10.c). Types 1 and 2 measure bending strain and type 3 measures axial strain. Only types 2 and 3 compensate for the Poisson effect, but all three types minimize the effects of temperature [8]. If four strain gauges are connected in Wheatstone bridge, it is called full bridge. Change of resistance is depending on the strain and in this case, it is calculated using full bridge first configuration.

\[
\Delta R = GF \cdot \varepsilon \cdot R \quad (1)
\]

The output voltage is calculated:

\[
U_f = \left[ \frac{R_1}{R_1 + R_4} - \frac{R_2}{R_2 + R_3} \right] \cdot U_i \quad (2)
\]

Where \( R_1, R_2, R_3, R_4 \) represent the electric resistance of individual strain gauge and \( U_i \) is input voltage.

The second simulation was done in form of calibration for the maximum load of 50 N. Nominal strain gauge resistance is \( R = 350 \, \Omega \) and gauge factor \( GF = 1 \) and for small strains, it is taken as constant. Usual input voltage for \( 350 \, \Omega \) gauges is \( U_i = 10 \, V \).

The error of force measurements in ideal conditions (assuming constant elasticity and gauge factor) gives the perception of imperfections of elastic element or simulation error which is low and construction can be considered adequate.
Table 3. Simulation of calibration [7].

| Input force [N] | Electrical resistance [Ω] | Output voltage [mV] | Output force [N] | Error   |
|----------------|---------------------------|---------------------|------------------|---------|
| 10             | 349.982 350.020 349.982 350.020 | 0.55                | 10.00011         | 0.0011% |
| 20             | 349.963 350.041 349.963 350.040 | 1.10                | 20.00016         | 0.0008% |
| 30             | 349.945 350.061 349.945 350.061 | 1.65                | 30.00016         | 0.0005% |
| 40             | 349.927 350.081 349.927 350.081 | 2.20                | 40.00012         | 0.0003% |
| 50             | 349.908 350.102 349.909 350.101 | 2.75                | 50.00000         | 0.0000% |
| 60             | 349.890 350.122 349.890 350.121 | 3.31                | 59.99970         | -0.0005%|
| 70             | 349.871 350.142 349.872 350.141 | 3.86                | 69.99964         | -0.0005%|
| 80             | 349.853 350.163 349.854 350.162 | 4.41                | 79.99928         | -0.0009%|
| 90             | 349.835 350.183 349.836 350.182 | 4.96                | 89.99895         | -0.0012%|
| 100            | 349.816 350.203 349.817 350.202 | 5.51                | 99.99856         | -0.0014%|

7. Further development plans
Smart supports are only a part of continuous project of equipping experimental mechanics lab. Firstly, computer application will be built as a companion to experimental device. Application will have two main functions:
- it will provide theoretical solution for set experiment,
- it will show real-time measurement of force reactions and possibly beam deflections at some points.

Companion software can be created using several platforms. The authors are considering following:
- Wolfram Mathematica to create an interactive application using manipulate function [10], connected with open source Arduino Uno board [11]
- LabView with NI data acquisition card is simpler but more expensive solution.

The experimental frame used for this project is designed in a way that enables building other modules for different experiments, which can be mounted on a frame when needed. Additional modules would be created as future undergraduate theses and upgraded through student projects.

All future experiments will be also equipped with sensors, connected to computer and companion software. This equipment is located in small space and the use in classes is limited, thus possibilities of building augmented reality distance learning tools will be investigated in the future.

8. Conclusion
An experimental sensor beam supports with an integrated load cell are based on strain gauge principle and can be used to create simply operated didactic devices. The use of strain gauge measurements proved to be extremely useful in the construction of measuring supports and their implementation is simple and commercially accessible. Strain gauges are relatively inexpensive, take a very little space and have a wide range of applications. Instead of strain gauges, it would be possible to use piezoelectric elements, but there would be a significant increase in cost. While measuring force, strain gauges are used on an elastic element. The construction of elastic element depends on its application. In this case, two different elastic element types are used (S-beam and double bending beam). Results of numerical simulation have shown that maximum force of 100N will not result with plastic deformation. The highest level of precision would be obtained if full Wheatstone bridge would be used. Such bridge is suitable for temperature and creep compensation. Using full bridge would also bring additional costs thus testing different configurations to find optimal setup would be advisable, especially in case of serial production. Errors could be partially eliminated using different materials and other types of elastic elements. Tests should be run on built supports in real use with different gauges. Testing of various gauges is advisable to achieve best results in durability and precision. The design of the supports is not entirely technologically elaborated and detailed evaluation of design should be done based on machining parameters. It should also be revised regarding beam positioning and centering problem.
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