

Design Of A Cost Effective Under Running Steel Girder Gantry Crane

STRESS ANALYSIS & DYNAMICS - ACMA5010
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Abstract

To ensure the safe operation of a gantry crane this report will determine an acceptable runway beam which will meet the required minimum second moment of area along with complying to current standards. There will be a comparison between theoretical calculations and 3D simulations to meet the maximum allowable 10mm deflection. To monitor the structural integrity of the beam, strain gauges can be used along with noting the history of strain gauges and how they have developed with what we can expect in the future. Finally, this report will suggest which strain gauge can be used and how they can be applied to this application to allow regular safe operation to occur.

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Introduction

Defining the second moment of area for a runway beam is critical to ensure the safety of operation when carrying out a 5000kg load lift. To ensure the maximum deflection of 10mm or less is achieved during this operation, a universal beam is to be specified which meets the requirements for this operation, as well as being in compliance to BS EN 10365:2017. Throughout the calculations multiple assumptions will be made to be able to meet the specified targets with the information provided. This report will show how theoretical calculations can be compared to analysis found within 3D modelling software, where simulation has a greater accuracy with the calculations being produced at a faster rate (Ghuku & Saha, 2020).

For monitoring the health of the beam, strain gauges are used to measure the bending strain occurring during the operation. These are very effective when positioned correctly. By using strain gauges, if there is an increased strain during the operation, it will highlight errors occurring which can be intervened and rectified before a catastrophic event occurs. Strain gauges are well established monitoring equipment and have developed over the years. With the constant development in technology over the years, it will enhance the way the overall health of the beam can be monitored.

Task 1 – Determining The Second Moment of Area

To ensure safe operation of a under running single girder, the maximum allowable deflection is restricted to 10mm when lifting a load of 5000kg. The component diagram is shown in figure 1. Firstly, the minimum second moment of area needs to be calculated to allow a suitable beam to be used as the beams second moment of area needs to be within the calculated limit for a maximum deflection of 10mm. By using the double integration method for a simply supported beam with a point load (Hearn, 1997), it allows the second moment of area to be calculated, where the equation is rearranged to make I_{xx} the subject, which I_{xx} is denoted as the second moment of area. *The full integrations calculations are shown in appendix A*, however the fully derived equation is as follows: (Hearn, 1997) (O'Rourke, 2016)

$$y_{max} = \frac{-W \cdot L^3}{48 \cdot E \cdot I}$$

Where;

y_{max} = The Maximum Deflection = 10mm

W = Is The Force Applied = -49050N

L = Length of beam = 10m

E = Youngs Modulus of Steel = 210GPa

I_{xx} = Second Moment of Area

With the rearranged equation:

$$I_{xx} = \frac{-W \cdot L^3}{48 \cdot E \cdot y_{max}}$$

With this rearranged formula and by using the subsequent numbers, the minimum second moment of area can be found. As the force on the beam is acting down on the y axis, this means the force is symbolised as negative, which in the equation is shown as '-W' whereby having a negative force these negative signs cancel leaving I_{xx} a positive answer (Erochko, 2015). *The full calculations can be seen in appendix B* however I_{xx} is equal to $48.66 \times 10^{-5} \text{ m}^4$.

In compliance to British Standard BS EN 10365:2017 Hot Rolled Steel Channels, I and H sections, a 533mmx210x92mm universal beam (Steel, 2017) has been calculated to complete this operation. To prove this beam can be used safely, the second moment of area can be calculated by taking the cross section of the beam on the x axis.

$$I_{xx} = \frac{BD^3}{12} - 2 \frac{bd^3}{12}$$

Where;

B = 209.3mm

D = 533.1mm

b = 99.6mm

d = 501.9mm

Using the above equation, the second moment of area for the beam is equal to $54.37 \times 10^{-5} \text{ m}^4$, which when compared to the minimum second moment of area previously calculated is above the minimum limit ($48.66 \times 10^{-5} \text{ m}^4$). Thus, this beam is adequate to use.

To ensure the accuracy of the calculations, the deflection can be recalculated to ensure when the load is being lifted, the deflection is still under 10mm when using the recommended beam. By using the deflection equation and using $I_{xx} = 54.37 \times 10^{-5} \text{ m}^4$ the deflection is equal to 8.95mm which is 1.05mm below the maximum allowable deflection for this operation, which proves this beam can be used for the safe operation of a 5000kg load. *The full calculations can be found in appendix E.*

Simulations can also be used to simulate how a beam reacts when a load is applied. This is shown in *figure 1* where the maximum predicted deflection for the proposed beam is $\pm 9.4\text{mm}$ which is 0.45mm different from the theoretical calculations. This proves how modern technology can provide quick and accurate simulations to ensure the safety on an operation.

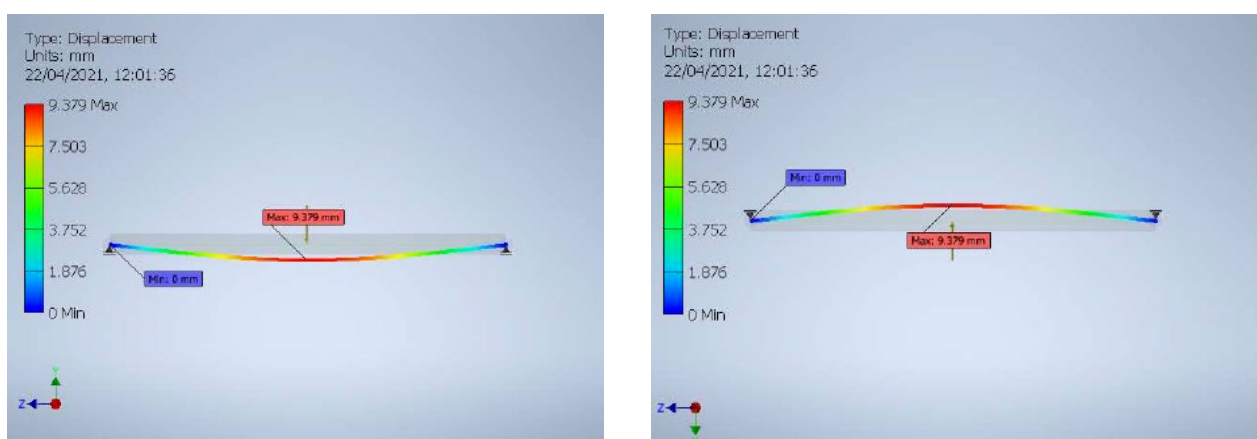


Figure 1 – Simulation of deflection occurring in a 533mmx210x92mm universal 10m beam with a 5000kg load.

Task 2 – Assumptions Made To Calculate The Second Moment Of Area

Throughout the first task, several assumptions have had to be made to ensure the deflection is within the maximum limit. Firstly, it has been assumed that the length of the beam is 10m in length, with the lift taking place within a sealed building meaning no live factors such as wind and snow can affect the amount of deflection occurring, as there are no live loads acting on the beam (Fanella, 2018). This is really important because if there were live loads acting on the beam, there would be an increase in force applied on the beam meaning the maximum deflection would increase.

The second assumption is the load is being lifted at the centre of the beam. This means the deflection is at its maximum point and if the load is to be lifted at an alternative position the deflection would be less (Hearn, 1997) (Collins, 2016) as shown in *figure 2* below. In the diagram, it is clear to see how the deflection decreases as distance from the centre increases. Due to this assumption, it has been assumed that the reaction forces are equal which would be calculated by $\text{Force}/2$ which equals 24,525N at each point, meaning zero deformation at boundary conditions.

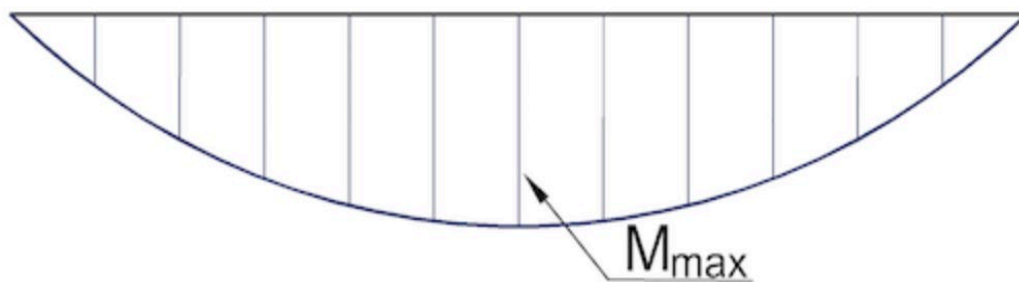


Figure 2 – Schematic showing the point of maximum deflection in a beam (ToolBox, 2009)

The third assumption is the beam orientation. This is critical because the orientation of the beam has a major impact of the second moment on area which will then affect the stiffness of the beam and affect the amount of deflection occurring as the force is acting on the Y plane of the beam. Figure 3 shows the two different types of orientations that can be used, both representing a shape of an 'I' and 'H' respectively. From task one the moment of inertia was found to be $54.37 \times 10^{-5} \text{ m}^4$, forming the shape of an 'I'. Whereas when the orientation is in the formation of 'H', the moment of inertia equals to $32.47 \times 10^{-5} \text{ m}^4$. By having the beam representing an 'I' shape, the second moment of area is 40% greater which would also make the stiffness of the beam 40% greater. This increase of stiffness in the beam decreases the amount of deflection occurring, where as in task one the deflection has been calculated to be 8.95mm and by having the beam in a 'H' shape, the deflection would be 15mm. *The full calculations can be found in appendix C & D.*

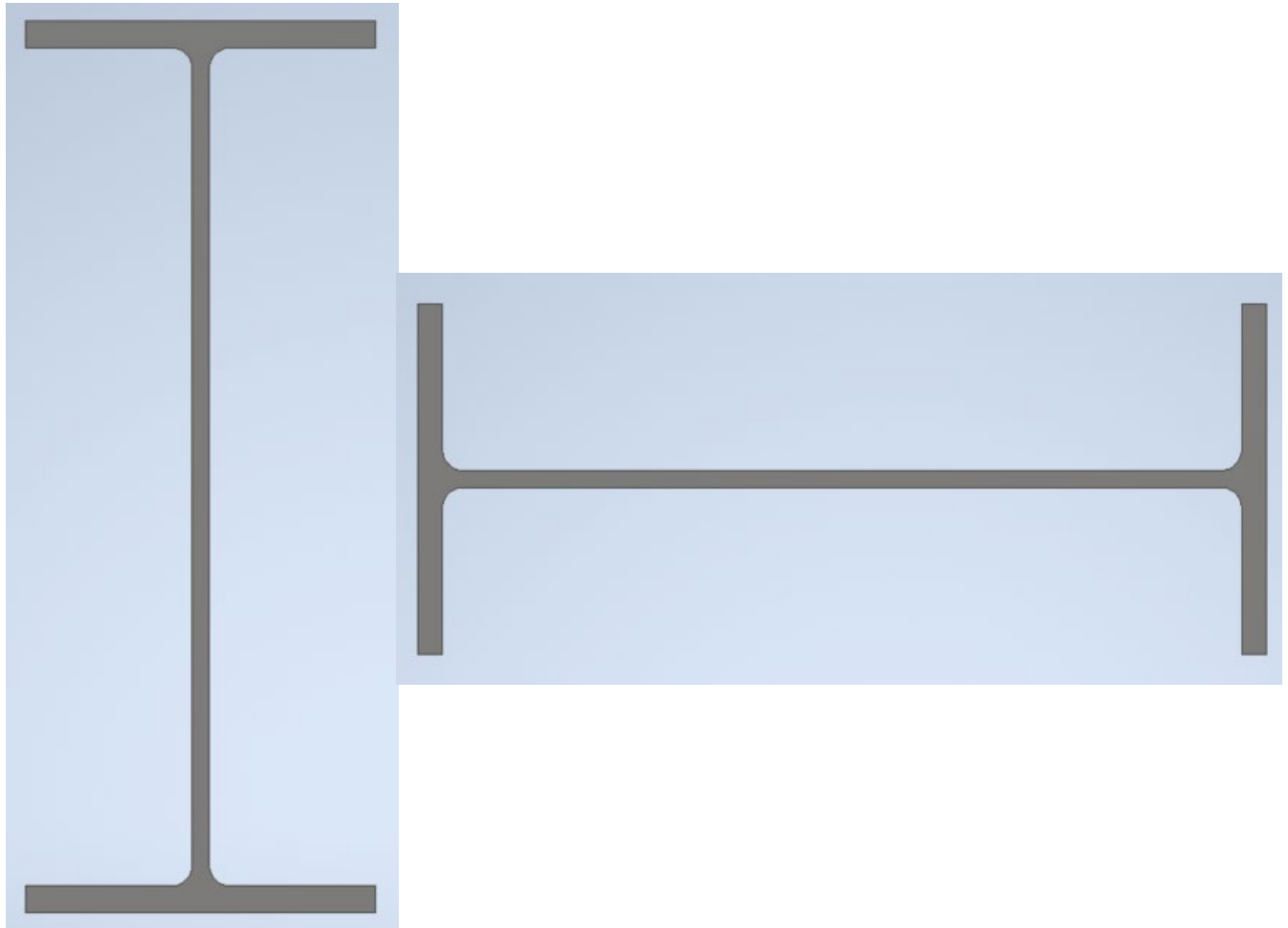


Figure 3 – Left image showing I representation and right image showing H orientation.

The fourth and final assumption made for the crane beam is that the deflection that has been calculated is static deflection. What hasn't been considered is dynamic deflection, where dynamic loading varies within its environment (Hunt, Zang, & Fu, 2012) (Raebel & Hayes, 2017) (Thomson, 2018). Compared to the lift speed being constant in respect to time, during static loading and only responds with displacement (Sparta, 2020) whereas dynamic loading has three types of responses, displacement, velocity and acceleration (Bohme, 2007). Where this difference is seen is when the load is being lifted. Static deflection would be seen when the load is being lifted at a constant rate, whereas dynamic deflection would be seen when the load is being started and stopped as there is a slight increase in acceleration, which would result in a greater force being applied on the beam (Sparta, 2020) (Bohme, 2007) (Raebel & Hayes, 2017). This results in an increase in deflection compared to the load being in a static state. Thus, a factor of safety would need to be implemented of 11% (Staff, 2016) which would take the maximum deflection occurring during this operation to 9.9mm which is 0.1mm under the maximum allowable deflection, when using all the calculated variables.

Task 3 – Strain Gauges

Strain gauges were first invented in 1938 by Arthur Ruge (United States Patent No. US2350972A, 1944). Strain gauges can be either used for obtaining information related to the forces occurring in a body, or to act as a measuring device for quantifying force, pressure, acceleration, tension and weight (Woodford, 2020). They have a resistance sensor which is dependent on the force applied where measurements are taken from a change in resistance (Omega, Strain Gauge - Introduction to Strain gauges, 2017) (Nachazel, 2020).

Back in the 1930's engineers could only use either mirrors or compound mechanical gauges, which measured strain using analogue gauges (Lieberman, Matz, & Rosegat, 2002). These gauges had a low accuracy as the force required to cause a change in measurement needed to be high, which is also known as the 'force of shift' (Bitannica, 2016) (Lieberman, Matz, & Rosegat, 2002). These gauges are relatively heavy, which added to inaccuracy of results due to fluctuating values occurring during dynamic loading.

There are several different types of strain gauges available which serve the majority of the industrial sectors. There are several designs for strain gauges, however the most common design is a metal strain gauge which is made up of a flexible polyimide film with a winding pattern of metal etched into the film, where copper-nickel alloy is commonly used material (Hoshino & Zhang, 2019). Typically, resistance will be measured between 30Ω and $3K\Omega$ (Circuits, 2019). The following describes the different types of circuits available to use.

Wire Resistance – This strain gauge is made of R_{gauge} where R_{wire1} , R_{wire2} and R_{wire3} connects to R_1 , R_2 and R_3 in the circuit. As the voltmeter connects to the centre of the terminal, R_{wire2} takes away any stray resistance that could potentially develop within the circuit (WilliamBolton, 2015) (Circuits, 2019).

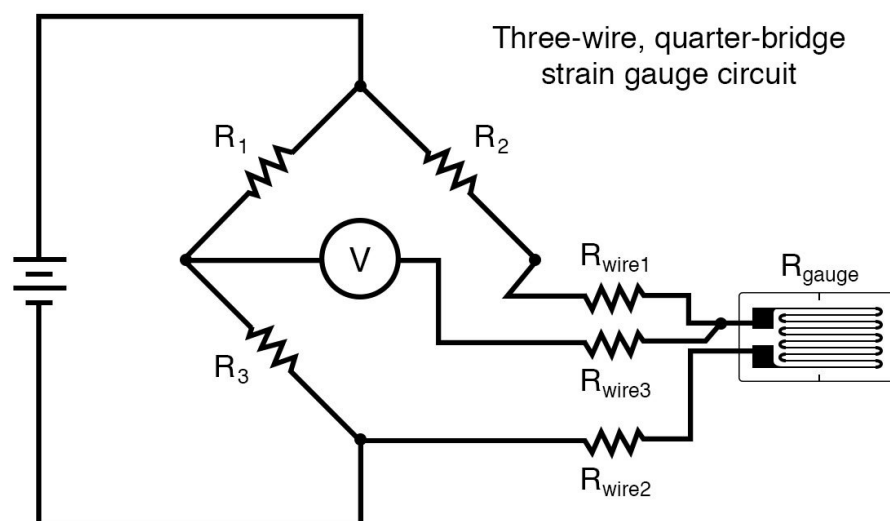


Figure 4 – Schematic of a wire resistance circuit (Circuits, 2019).

Quarter Bridge and Half Bridge Circuits – A quarter bridge circuit includes two strain gauges in the circuit while only one is responsive to mechanical strain. To utilise this set up, the upper gauge would need to be positioned to be exposed to the opposite force of the lower gauge. This results in both gauges reacting to strain which making the bridge sensitive to the force being applied as the upper gauge compresses and the lower gauge stretches (Hanson, 2020) (Ni, 2020).

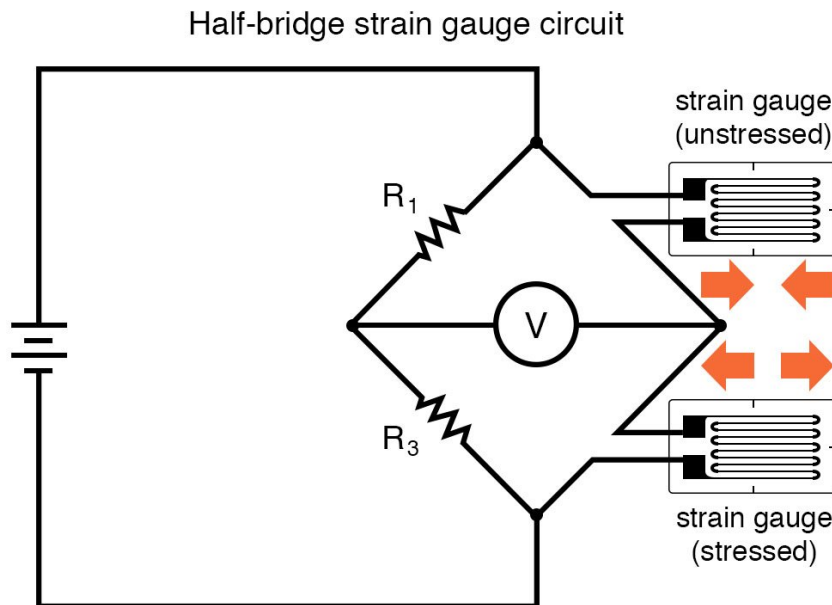


Figure 5 – Schematic of a half bridge circuit (Circuits, 2019).

Full Bridge – This circuit consist of four strain gauges in similar orientation to a half bridge circuit. The output voltage is directly proportional to force applied for this circuit, whereas in a half bridge circuit the output is approximately proportional to the applied force. This allows more precise readings to be taken and problems can be seen by the voltage in gauges become unbalanced (Stano & Peroco, 2020).

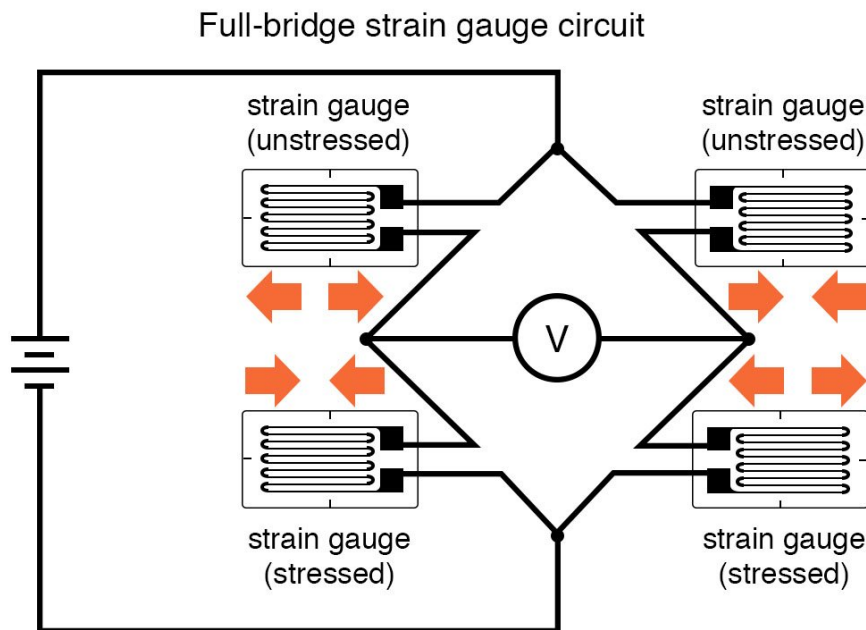


Figure 6 – Schematic of a full bridge circuit (Circuits, 2019).

Rosettes – Membrane rosette strain gauges measure displacement, velocity, pressure and force. They can also measure elastic strain occurring in a body when using static and dynamic loads, measuring in an equilateral triangle orientation (Hollings, 2021) (HBM, What is a Strain Gauge Rosette?, 2018).

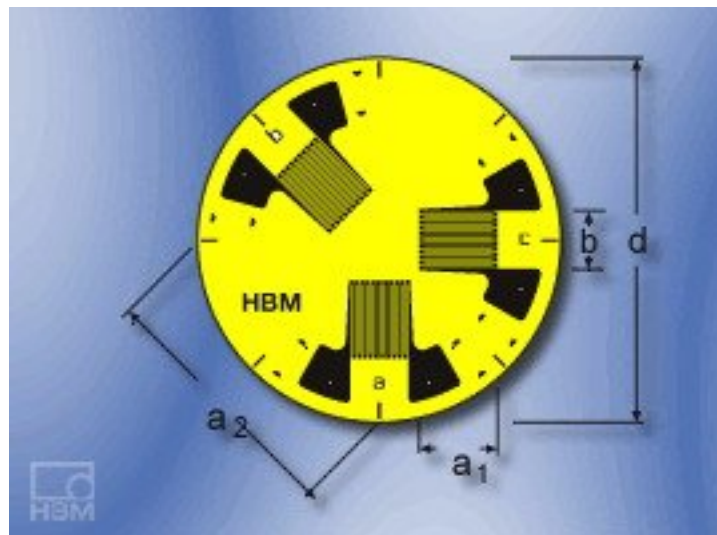


Figure 7 – Schematic of a rosette circuit (HBM, What is a Strain Gauge Rosette?, 2018).

Future of strain gauges

While strain gauges have been imperative to engineers across the industrial sector, there is new technology which will allow live data recording from all round the world to take place, which incorporates with industry 4.0. This technology is fibre Bragg grating (FBG) which is a fibre optic sensor that can measure all the data points that a strain gauge can measure and more. Strain gauges are typically limited to measuring one parameter at a time, however, with FBG, more than eight parameters can be measured using this technology (Xu, Ren, & Wang, 2016). This technology isn't just limited to measuring strain or deflection in a frame, but it can also measure the full health of the frame to ensure no defects are occurring in structures.

By using FBG, there is now the potential to widen data collection. Where strain gauges can only operate within -75C to 200C, FBG can operate between -250C and 700C which would allow more data being recorded from different applications. However, strain gauges have a better strain range of ± 30000 micro strain (Omega, STRAIN GAGE TECHNICAL DATA, 2017), whereas FBG can only measure between ± 20000 micro strain (Birch, 2013). As FBG is relatively new technology, with the current advancement of industrial technology this strain range will increase. Likewise, the price of a strain gauge is low compared to FBG being high, and with newer technology, this price will decrease.

Task 4 – Application of Strain Gauges

To be able to regularly monitor the performance of the proposed beam, full bridge strain gauge can provide the relative and necessary information. As previously mentioned, this type of strain gauges allows the bending strain to be measured and the optimum position of the gauges is at the centre of the beam. There should be two strain gauges positioned on the top flange (R1 & R3) of the beam and two gauges (R2 & R4) on top of the bottom flange of the beam (Omega, STRAIN GAUGE INSTALLATION HOW TO POSITION STRAIN GAUGES TO MONITOR BENDING, AXIAL, SHEAR, AND TORSIONAL LOADS, 2017). By positioning the gauges in the centre of the beams, the monitoring can ensure the beams maximum stress points are being measured by measuring the bending strain during the lift. To enhance data collection, multiple series of circuits can be placed on the beam while recording the distance from either the centre or from the face of the beam. To bond the gauges to the beam, the adhesive of the gauge needs to be cured with curing glue while applying force on to the gauge to help adhesive cure to the beam (HBM, Task and Function of the Bonding Material, 2020). This process will take less than five minutes then the gauges need to be connected to a voltmeter and then these gauges are ready to use. The arrangement of the strain gauges can be shown in figure 7. When the voltage is applied to the circuit R1, R2, R3 and R4 should be equal as there shouldn't be any potential difference between the voltage points on the Wheatstone bridge circuit. There are two ways to which the deflection can be measured from the strain gauges. The first being a traditional way to convert the bending strain voltage into the strain equation to find the change in displacement. Secondly, there are now displacement transducer sensors that can be applied to the circuit to automatically change the voltage recordings into a readable deflection measurement.

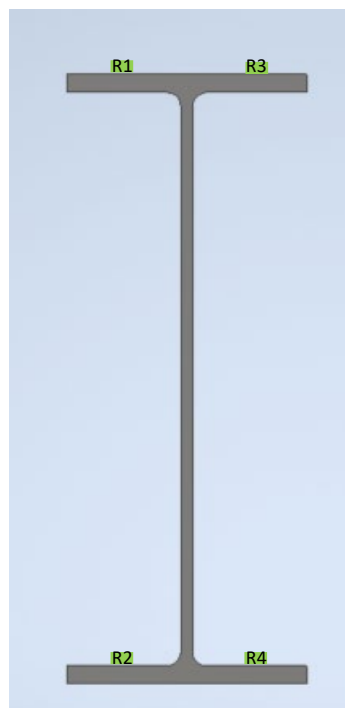


Figure 8 – Schematic of strain gauges connected to I beam.

By using these methods, it allows engineers to accurately monitor the health of structural beams to ensure they are performing to the expected standards. For any reasons, if there is an increase in the strain then this would result in an increase in deflection where it would allow maintenance to take place on the beam to prevent any catastrophic failure occurring in the beam.

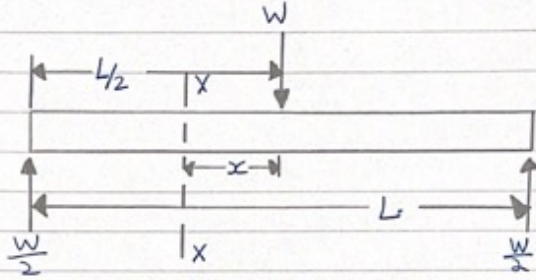
Conclusion

Ensuring the maximum deflection of 10mm is met, it is critical that the beams cross sectional area is greater than the minimum second moment of area required for a 10m length beam. If this value is less than the minimum required, then the maximum deflection would increase. It is also important that the beam orientation is in its optimum orientation, representing an 'I' shape instead of an 'H' form. By having the beam in an 'I' position, the second moment of area is greater, which increases the stiffness of the beam, resulting in less deflection occurring in this orientation. Thus, a 533mmx210mmx92mm beam needs to be used to suit the maximum deflection required, where the static deflection would be 8.95mm and with a factor of safety of 11% taking the dynamic deflection to 9.9mm.

To monitor the beams health, full quarter strain gauges can be used to measure the beams bending strain to allow the deflection of the beam to be calculated. If the resistance increases, it will imply a failure occurring. With new technology of fibre Bragg Grating this process of monitoring strain and deflection can be improved by gathering live and constant data, as this technology can measure several parameters where a strain gauge can only measure one parameter. This ensures any defects that occur in a structure are seen early and can be rectified before a catastrophic event occurs.

Appendices

Appendix A – Derivations For The Double Integration Method



The moment at XX is given by $\frac{W}{2} \left(\frac{L}{2} - x \right)$ therefore;

$$\frac{WL}{4} - \frac{Wx}{2} = EI \frac{d^2y}{dx^2}$$

$$EI \frac{dy}{dx} = \frac{WLx}{4} - \frac{Wx^2}{4} + A \quad \text{and}$$

$$EIy = \frac{WLx^2}{8} - \frac{Wx^3}{12} + Ax + B$$

Since we know that when $x=0$ the slope is zero;

$$A=0$$

We also know that when x is $L/2$ the deflection is zero;

$$B = -\frac{WL^3}{48}$$

Therefore the deflection at all point on the beam is given by;

$$y = \frac{1}{EI} \left[\frac{WLx^2}{8} - \frac{Wx^3}{12} - \frac{WL^3}{48} \right]$$

Since the maximum deflection happens when $x=0$;

$$y_{\max} = \frac{-WL^3}{48EI}$$

Appendix B – Minimum Second Moment of Area Calculations

$$y_{\max} = \frac{-WL^3}{48EI}$$
$$y_{\max}(48EI) = -WL^3$$
$$48EI = \frac{-WL^3}{y_{\max}}$$
$$I_{xx} = \frac{-WL^3}{48Ey_{\max}}$$
$$I_{xx} = \frac{-WL^3}{48Ey_{\max}}$$

Where:

$$W = -49050 \text{ N}$$
$$L = 10 \text{ m}$$
$$E = 2.1 \times 10^{11} \text{ Pa}$$
$$y_{\max} = 0.01 \text{ m}$$
$$\therefore I_{xx} = \frac{-(-49050)(10^3)}{48(2.1 \times 10^{11})(0.01)}$$
$$I_{xx} = 0.00048661 \text{ m}^4$$
$$I_{xx} = 48.66 \times 10^{-5} \text{ m}^4$$

Appendix C – Second Moment of Area for A 533mm x 210mm x 92mm I Beam

BS 4-1: 200S 533mm x 210mm x 92mm

Where;

$B = 209.3 \text{ mm}$
 $D = 533.1 \text{ mm}$
 $T = 15.6 \text{ mm}$
 $t = 10.1 \text{ mm}$
 $r = 12.7 \text{ mm}$
 $b = \frac{B}{2} - \frac{t}{2} = \frac{209.3}{2} - \frac{10.1}{2} = 99.6 \text{ mm}$
 $d_1 = 533.1 - (15.6 \times 2) = 501.9 \text{ mm}$
 $d_2 = 476.5 \text{ mm}$

$$I_{xx} = \frac{BD^3}{12} - 2\left(\frac{bd_2^3}{12}\right) = \left[\frac{209.3(533.1)^3}{12}\right] - 2\left[\frac{99.6(501.9)^3}{12}\right]$$

$I_{xx} = 543,749,118.9 \text{ mm}^4$
 $I_{xx} = 0.00054374911 \text{ m}^4$
 $I_{xx} = 54.37 \times 10^{-5} \text{ m}^4$

Appendix D - Second Moment of Area for A 533mm x 210mm x 92mm H Beam

BS4-1: 2005 533mm x 210mm x 92mm

Where;

$B = 533.1 \text{ mm}$
 $D = 209.3 \text{ mm}$
 $T = 15.6 \text{ mm}$
 $t = 10.1 \text{ mm}$
 $r = 12.7 \text{ mm}$
 $d_1 = \frac{D}{2} - \frac{t}{2} = \frac{209.3}{2} - \frac{10.1}{2} = 99.6 \text{ mm}$
 $b_1 = 533.1 - (15.6 \times 2) = 501.9 \text{ mm}$
 $b_2 = 476.5 \text{ mm}$

$$I_{xx} = \frac{BD^3}{12} - 2 \left(\frac{b_1 d_1^3}{12} \right) = \left[\frac{(533.1)(209.3^3)}{12} - 2 \frac{(501.9)(99.6^3)}{12} \right]$$

$I_{xx} = 324,669,214.7 \text{ mm}^4$
 $I_{xx} = 0.000324669214 \text{ m}^4$
 $I_{xx} = 32.47 \times 10^{-6} \text{ m}^4$

Appendix E – Deflection Calculations for A 533mm x 210mm x 92mm I Beam

$$y_{\max} = \frac{-WL^3}{48EI}$$

Where;

$$W = -49050 \text{ N}$$

$$L = 10 \text{ m}$$

$$E = 2.1 \times 10^{11} \text{ Pa}$$

$$I = 54.37 \times 10^{-5} \text{ m}^4$$

$$y_{\max} = \frac{-WL^3}{48EI}$$

$$y_{\max} = \frac{-(-49050)(10^3)}{48(2.1 \times 10^{11})(54.37 \times 10^{-5})}$$

$$y_{\max} = 0.00895 \text{ m}$$

$$y_{\max} = 8.95 \text{ mm (2dp)}$$

Appendix F - Deflection Calculations for A 533mm x 210mm x 92mm H Beam

$$y_{\max} = \frac{-WL^3}{48EI}$$

Where;

$$W = -49050 \text{ N}$$

$$L = 10 \text{ m}$$

$$E = 2.1 \times 10^{11} \text{ Pa}$$

$$I = 32.47 \times 10^{-3} \text{ m}^4$$

$$y_{\max} = \frac{-WL^3}{48EI}$$

$$y_{\max} = \frac{-(-49050)(10^3)}{48(2.1 \times 10^{11})(32.47 \times 10^{-3})}$$

$$y_{\max} = 0.014988 \text{ m}$$

$$y_{\max} = 14.99 \text{ mm (2dp)}$$

$$y_{\max} = 15 \text{ mm (2sf)}$$

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