Structural and Instrumentation Design of a Force Sensor in a Railway Coupler

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Abstract: The traction power is the main quantity to identify the railway train capacity. Train performance is a function of the locomotive force over the train weight ratio. One easy way to measure the locomotive traction force is to use the standard railway coupler. Due to its mechanics conception, the standard coupler main body has an irregular shape that produces non-homogeneous stress distribution when loaded. Additionally, the force application point changes with the working conditions (traction/ compression) and the wagon type, the size and the relative movements. The motivation of this work consists on the design of an instrumented coupler to act as a force sensor, with a minimum cross talk effect to the described non-desirable phenomenon. The instrumentation is performed with electric strain gages bounded in the coupler structural body. The main difficulties are those related to the identification of the appropriate localization for the instrumentation, the maximum structural strain magnification and the optimised thermal compensating deviation and over all the linear performance. The structural elastic sensor design has been implemented throughout the finite element technique to choose the appropriate location to apply the instrumentation with homogeneous stress and moment free cross talk effect. The traditional hole-in-a-plate stress concentration effect is used for magnifying strain purpose. Wheatstone bridge arrangement is used to avoid any undesired lack of structural symmetry and thermal compensating purpose.

Keyword: force sensor, instrumentation, railway, coupler

1. Introduction

The longitudinal train dynamics involves several operations, including acceleration, braking, etc. The forces in this direction influence the efficient, the safe and the stable operations of the train, thus, it is very important to measure them. The railway couplers are the longitudinal components responsible for the coupling between the railway vehicles, as we can see in Figure 1). There are a lot of different types of coupler, each one developed to a certain application. Using this equipment it is possible to verify the traction system of the railway train and it has been used for several years. Therefore there are some problems involving this measure. One is the difference between the traction and compression calibration curve, most times around 30%, that indicates that is not linear. The other problem is the influence of the moments in the measure that can cause a wrong interpretation of the data acquired.

Figure 1 . Coupling between railway wagons.

2. Theoretical Fundamentals

2.1. Finite Elements

The finite elements method (FEM) is a solution based on an integral of a function, as shown in Spyrakos (1994). Basically, its solution is an approach made for polynomials defined in the discretization of the system; Therefore, the FEM is not an accurate method, but brings solutions of high precision when used correctly.

The procedure of the FEM consists basically on structuring the system in a matricial form, on applying boundary conditions and then solving the system.

The matricial system to be solved is:

$$[K]*\{u\}=\{F\} \tag{1}$$

where [K] is the rigid matrix; {u} is the displacement vector; {F} is the forces vector.

2.2. Functional Project

For the coupler analysis we need to know the forces and moments involved on the longitudinal direction. Giacaglia (1982), shows that when an external force is applied into any direction, the internal forces will balance the external forces. These internal forces can present different magnitudes and directions, but they can be decomposed in parallels and perpendiculars components.

As our purpose is to measure exclusively the longitudinal forces in the coupler, we have to minimize the moments' effects over the instrumentation area.

Making the free body diagram we can check the efforts and the reactions involved.

If we have a perfect coupling, the force will be on the neutral line of the coupler, and a force in the restrain will balance the external force, which is the force of the other coupler. Therefore, in a real coupling we have two moments that can happen. One in the direction z, if the centerlines of the wagons are not aligned, and another in the direction y, due to the difference of height between the wagons. In Figure 2), one can see the perfect coupling and a coupling with a moment in direction z. This two moments influence the distribution of the stress on the coupler, therefore the interest of the analysis of this case in the present study

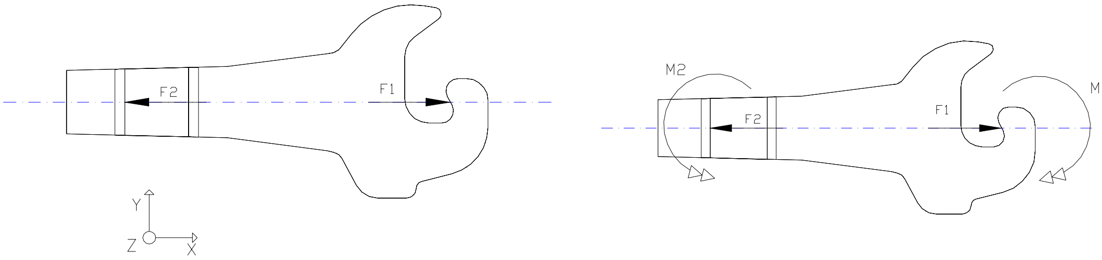

Figure 2 . Forces involved on the coupling

The static balance would be :

$$\sum F=0 \tag{2}$$

$$F1=F2 \tag{3}$$

$$\sum M=0 \tag{4}$$

$$M1=M2 \tag{5}$$

$$M1=F1*d \tag{6}$$

$$\sigma_x=\frac{F}{A}+\frac{M*y}{I} \tag{7}$$

where

d is the distance between the point of the force application and the neutral line; F1,F2,F are forces; M,M1,M2 are moments; A is the transversal area; y is the distance between the point where we calculate the stress and the neutral line of the area; I is the inertia of the transversal area; σ_x is the stress in x direction.

The analysis is analogous for the moment in y direction.

2.3. Geometrical Model

In order to facilitate the finite elements analysis the real model of the coupler can be simplify. The coupler type F was used on this study because is one of the most used in railroads in Brazil. Its basic dimension was taken of the American railway standard – AAR (1978).
The most important details are those who are not symmetrical according to the neutral line, the others can be omitted. As the study is qualitative, the main importance is to maintenance the proportion between the dimensions, not the dimension itself.
To make the FEM analysis it is necessary to make the geometrical model. This can be done using drawing software that is compatible with the FEM software. In this case, AutoCad® was used.
The geometrical model it is shown in Figure 3).

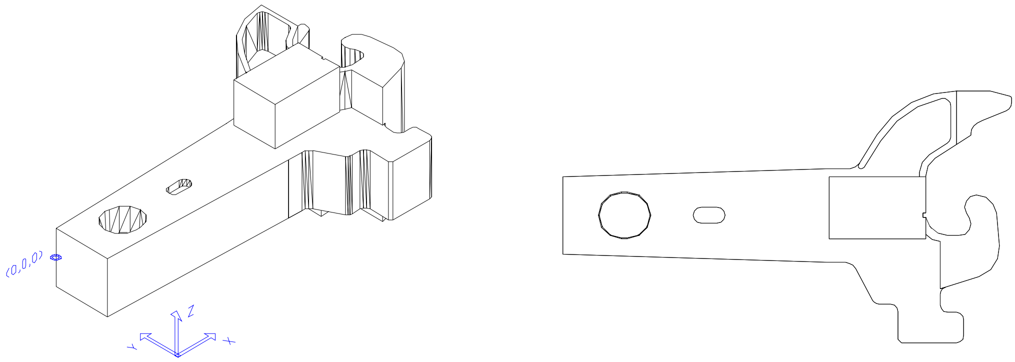

Figure 3 . Geometrical model of the coupler

2.4. Finite Elements Analysis

The numerical program used for the finite elements analysis was the Cosmos/DesignStar®. This program uses some automatic standards, as type of elements, tetrahedrals, and as restrains that can be applied only over surfaces or edges. Therefore, its use becomes restricted, but for a 3D model the tools available are satisfactory. To make the FEM analysis using this software these steps must be followed: define the geometrical model, begin a static study, define the material properties, define boundary conditions, define the mesh, and define the size of the elements. The elements size used was 25 mm, and on the trapezoidal region of the coupler the elements had 10 mm of size. After the numerical processing, the results of the stress may be analysed in any direction.

2.4.1.Efforts and boundary conditions

For the traction load it was applied 10000N normal to the face were the other coupler would couple as it can be seen in Figure 4). The boundary condition is fixed, similar to the force that the pin would apply against the hole. Due to the fact that the hole is not a perfect cylinder we have a small area of contact.
For the compression load it was applied -10000N normal to the face of the contact with the other coupler, Figure 5). The boundary condition is the same of the traction but in the opposite side.

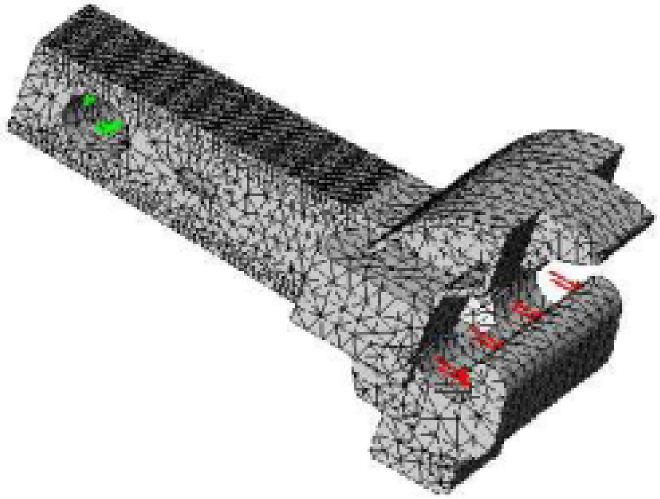

Figure 4 . Mesh and boundary conditions for traction load.

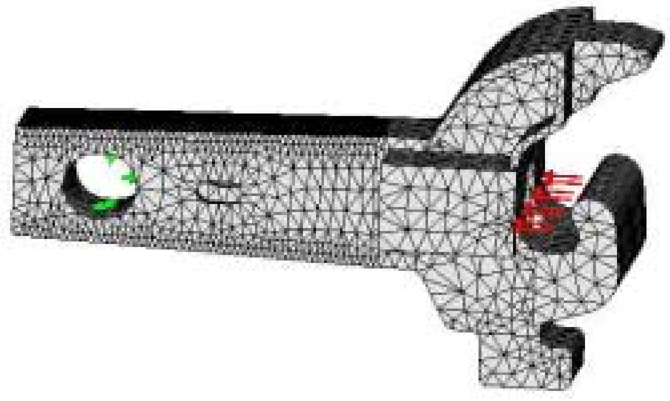

Figure 5 . Mesh and boundary conditions for compression load.

For the moment load in direction y it was used two forces of 5000N each one as is Figure 6). That case would be equivalent to the maximum moment one force of 10000N can cause. The boundary condition is opposite to the force, and it is equivalent to the real restrain.

For the moment load in direction z, Figure 7) the boundary conditions and the force is analogous to the moment in direction y, but in the plane xy.

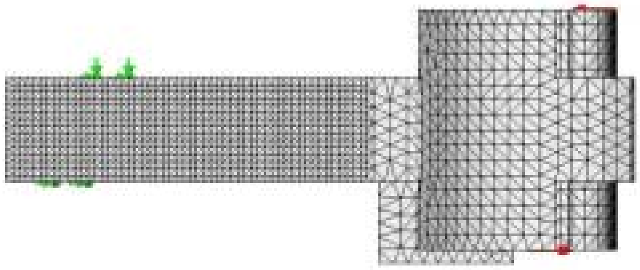

Figure 6 . Mesh and boundary conditions for moment load applied in direction y.

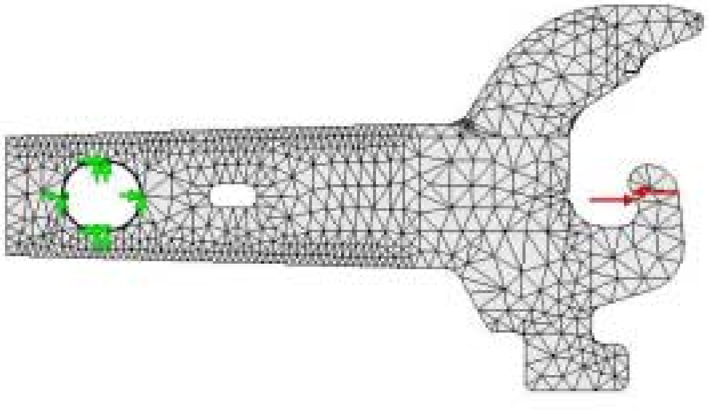

Figure 7 . Mesh and boundary conditions for moment load applied in direction z.

3. Results

It can be seen in Figure 8) and in Figure 9) that for traction and compression loads, the stress distribution in the coupler is irregular. In this study we intend to find a region where this distribution is not so irregular and the values of traction and compression are as similar as possible.

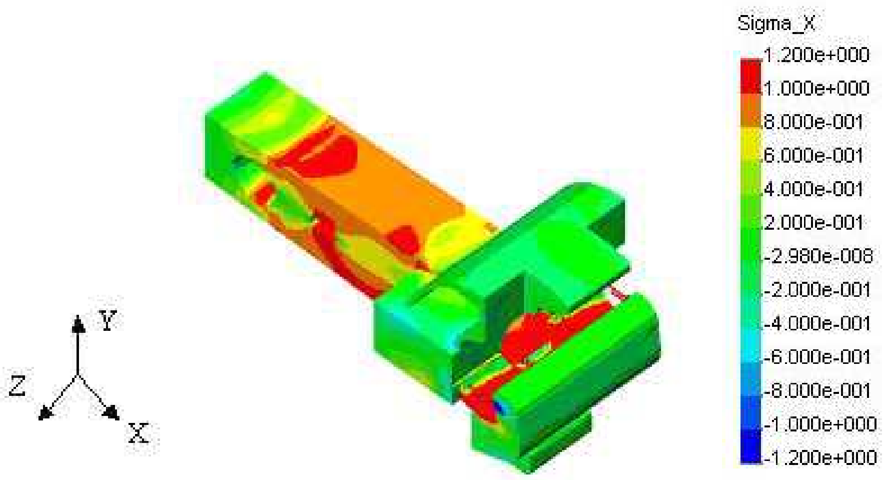

Figure 8. Results stress in direction x for traction load.

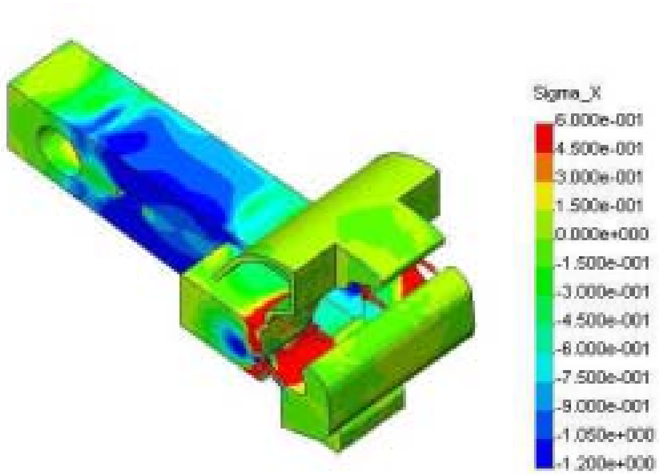

Figure 9 . Results stress in direction x for compression load.

The faces along the direction y have a distribution of stress more linear than the other faces, so these faces were chosen for a closer analysis.

For results of the moment in direction y, Figure 10), it is intend to find the place for instrumentation where the stress result is symmetrically opposite, so it can be annulled. An appropriate way to do this is to arrange the instrumentation symmetrically distant of the neutral line. The neutral line calculated from the known dimensions is 0,1851” distant of the geometrical center of this face in the direction of the largest wall of the coupler.

For the result of the moment load in direction z, Figure 11) it is observed that the faces along the xz plane have stress of opposite values, so if we sum these values we can cancel the effect of this moment.

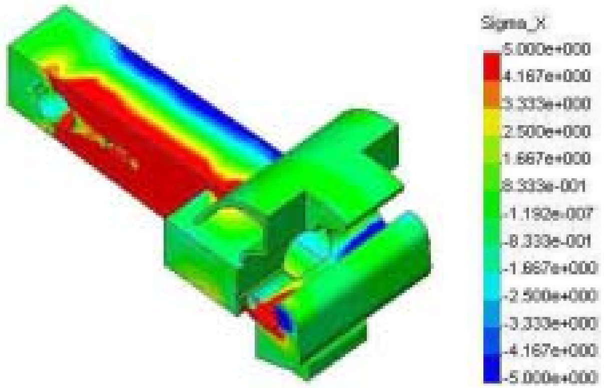

Figure 10 . Results stress in direction x for moment load applied in y direction.

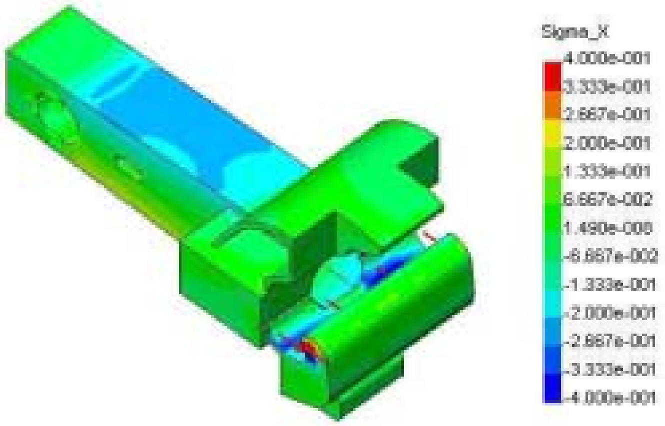

Figure 11 . Results stress in direction x for moment load applied in z direction.

4. Instrumentation

The region chosen for the instrumentation was the lateral face along the xz plane and it is near the middle of the trapezoidal region. Earlier experiments showed that the sensibility of the instrumentation of the coupler is very low and thus it is necessary to use amplification that can introduce interferences in the system. In order to increase the sensibility it was made a hole in the coupler, so the stress will be increased in approximately three times as shown in Timoshenko (1959) in Figure 12). The final position chosen it is shown in Figure 13).

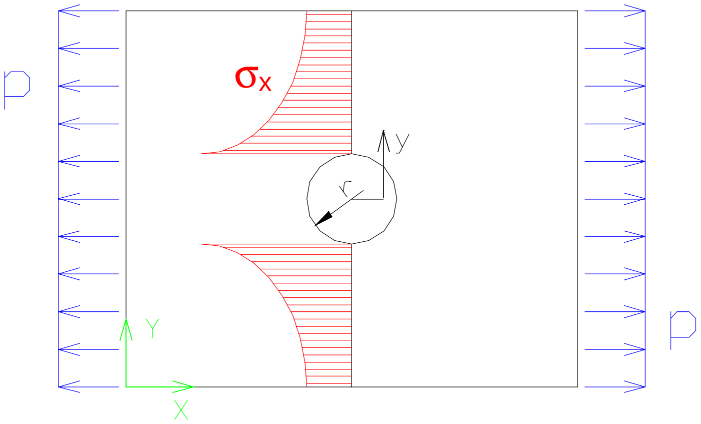

Figure 12. Stress concentration due to a hole in a plate.

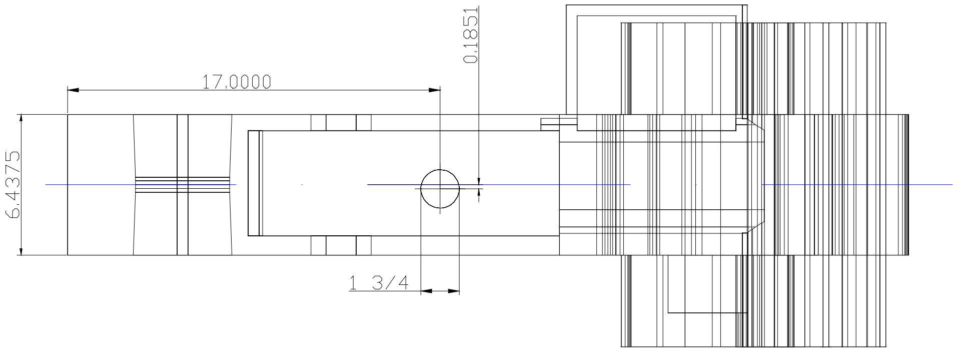

Figure 13. Position chosen for the instrumentation.

In order to validate the importance of the hole in the coupler the geometrical model with the hole was used for a FEM again. The procedure is the same but in this case it was used a mesh with elements of 2mm of size near the hole, for a better result.

4.1. Results of the FEM

The results showed in Figure 14) confirm that the hole in the coupler can increase the sensibility without affecting the linearity in the measure. Because of the fact that the centre of the hole is the centre of mass of the coupler, the stress in places diametrically opposites are symmetrical and thus the influence of the moments can be annulled as it can be seen on Table (1).

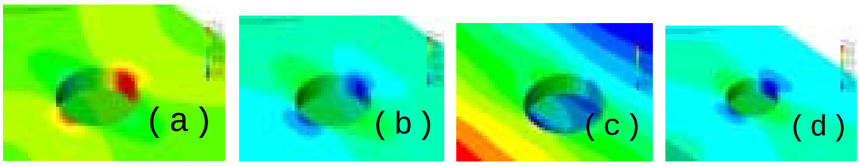

Figure 14 . Results stress in direction x for traction (a), compression (b), moment y (c) and moment z (d) loads.

Table 1 . Results of FEM for stress on direction x.

STRESS ON X DIRECTION							
Coupler with the hole for instrumentation position:						Force:	10000 N
X (in)	Y(in)	Z (in)		Traction (Mpa)	Compression(Mpa)	MY (Mpa)	MZ (Mpa)
17.00	0.22	0.69		2.95	-3.03	2.01	-0.30
17.00	0.22	-1.06		2.90	-2.64	-1.79	-0.31
17.00	-6.82	0.69		2.94	-3.01	2.05	0.31
17.00	-6.82	-1.06		2.71	-2.50	-2.24	0.31
			sum :	11.49	-11.18	0.03	0.00
				influence of the moments (%)		0.24	0.03
diference between traction and compression (traction+compression/traction):							
2.68		%					

A better illustration of the symmetrical effect of the stress on the hole can be seen in Figure 15).

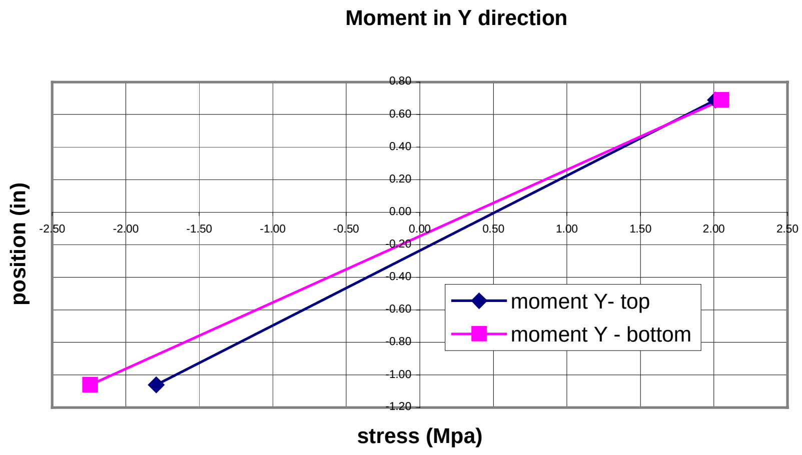

Figure 15. Result of load moment applied in y direction on the hole in the coupler.

4.2. Configuration of the instrumentation

The sensor chosen for the instrumentation was the electric strain-gage that identifies deformation that can be correlated to the force. As shown in Hoffmann (1989), when the length of a resistor changes, its resistance changes proportionally, due to this effect we have a linear relation between resistance and deformation and it can be measure in volts if we apply some current into it. The relation between the difference in the resistance and the difference in the length of the gage it is called sensibility factor, or just k. So, the force can be measure by a relation curve between electric voltage and force that we called calibration curve.

For less influence of the stress variation in the hole the sensor must be as short as possible so we can have most punctual values as possible, linear and stable, among other properties. For this study a sensor with 5mm of size was chosen because it can give good results compare to its cost.

In order to measure the tension we use the Wheatstone bridge. According to Dally (1991), it measures the relative changes in the resistance and therefore in the tension also. The circuit it is shown in Figure 16).

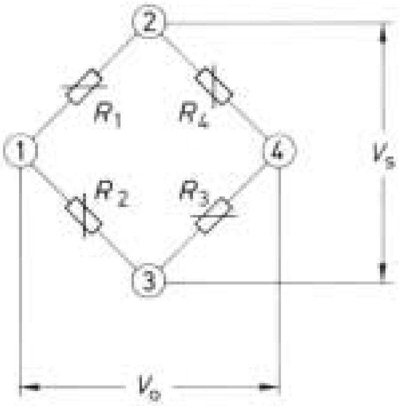

Figure 16. Basic circuit of the Wheatstone bridge

And the principle of measurement is:

$$\frac{V_0}{V_S} = \frac{k}{4} * (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \qquad (8)$$

k = 2.

For this design the best configuration is the half bridge. The full bridge with strain-gage in transversal direction in the hole would give bigger difference between traction and compression (due to lack of symmetry in the stress distribution) with an increase of only one third of the bridge sensibility. For compensating the temperature it was used four dummies connected to a plate not physically connected to the coupler deformation.

The Wheatstone bridge for the coupler it is shown in Figure 17).

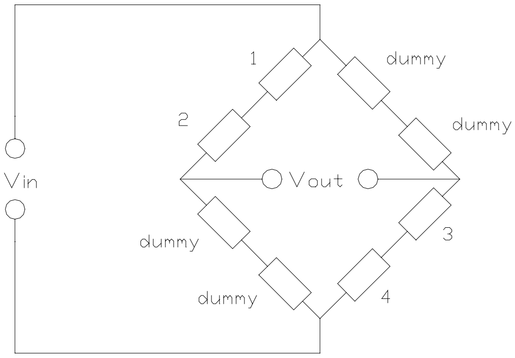

Figure 17. Design of the Wheatstone bridge.

5. Conclusion

Using the finite elements analysis it could be done a mechanical project for the sensor. The project methodology developed for this work showed itself very useful and it can be applied to solve other types of instrumentation problems. Due to the irregular distribution of the stress on the faces of the coupler, the best region to apply the instrumentation would be on the lateral faces, along the axis y, instead of along the axis z, used in earlier experiments. On account of the great variation of stress on the faces, the best region would be between the head of the coupler and its hole for the fixation. Making a FEM with the instrumentation design proposed, the positioning and the configuration of sensors, we can reach a difference between traction and compression on the calibration curve under 3%, around 10 times better then earlier experiments and the cross talk influence of the moments on the measurement will be under 1%, affirming that the results measured with this configuration of instrumentation are reliable.

6. Acknowledgements

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