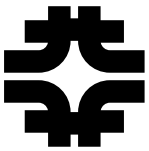

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LHC IRQ Cryostat Support Mechanical Performance

Ch. Darve, T. Nicol and A. Knauf

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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LHC IRQ Cryostat support mechanical performance

Ch. Darve, T. Nicol, A. Knauf

Keywords: LHC IRQ support, numerical model, strain gauge, displacement measurement, glass fiber material

Abstract

The LHC Interaction Region Quadrupoles (IRQ) will be shipped from Fermilab to CERN. The IRQ magnets are supported by glass fiber supports. A prototype cryostat support has been tested under various mechanical forces in order to check its mechanical behavior. These measurements have been made in order to validate a numerical model. A large range of mechanical loads simulates loads due to the shipment of the device, the weight of the cold mass as well as the cool down conditions. Its mechanical properties are measured by means of a dedicated arrangement operating at room temperature.
This study appears to be essential to optimize the design of the support.
The purpose of this note is to summarize the first measurements related to mechanical tests performed with the support.

1 Introduction

One IRQ cryostat support had been tested under various mechanical forces in order to check its mechanical behavior. The test arrangement enables measurements of displacements and strains of support components for the simulation of various mechanical conditions: shipping, handling, and operation. The present test will validate and improve a finite element model dedicated to the simulation of the mechanical behavior of the support as well as the cool down conditions.

2 Cryostat support function

The supports are located at two places in each 7 meter-long IRQ cryostat. Their function is to support the cold mass in the vacuum vessel.
Operational temperatures of the support and the high weight of the cold mass necessitate the use of a stiff and low thermal conducting material. Glass fiber composite (G11) is a perfect candidate and will limit heat inleaks from the room temperature vacuum vessel to the 2K cold mass.
The cold mass is linked to the support by two stainless steel pins (fig 3a). Stainless steel hollow lugs (cold mass attachment lugs) are located at the interface between the fiberglass spider and the pins.
Cylinder lugs (lugs/ref) are located at the interface between the support and the vacuum vessel in order to block the support.
An aluminum thermal shield will be fastened to the stainless steel bands, itself screwed and glued to the G11 plate.
The estimated allowable stress is 25,000 psi.

3 Numerical analysis

3.1 Description

A thermo-mechanical finite element model was generated using ANSYS.
The geometry of the model is based on the design, in Fermilab drawing 5520 ME – 364219.
The 2D and 3D chosen elements are plane42 and solid45, respectively.
Material properties used are listed bellow:

G11:	E= 3E6 psi,	NXY=0.3,	GXY=385,000 psi
Stainless Steel:	E= 28E6 psi,	NXY=0.3	

The support is rigidly attached to the vacuum vessel using four lugs/ref (fig. 3a), consequently the boundary conditions induce no displacement at these positions.

The load is applied on the two stainless steel lugs. In so far as the model is linear, we only studied the case of 1,000 lb force homogeneously distributed on the nodes of the cold mass attachment lugs.
The loads studied are those due to shipping, handling, and cool down.
Displacements and strains are analyzed using the ANSYS post-processor.

3.2 Results

The following figures illustrate some of the distribution of displacement and strain for various load configurations.

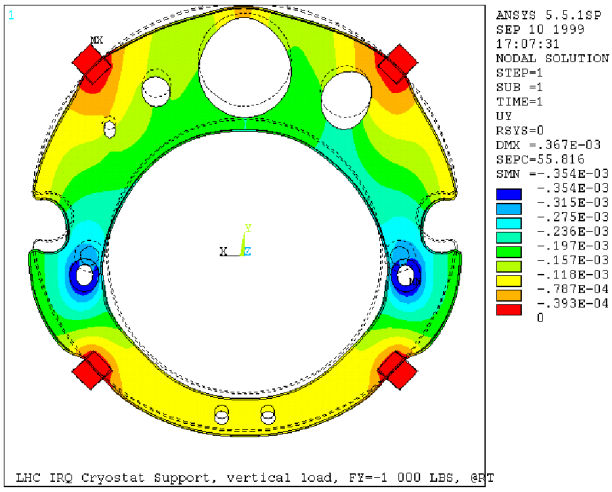

Figure 1: Example for a load applied vertically (Y-axis) (simulation of the displacement along the y-axis due to the weight of the cold mass)

<u>Load</u>:
FY_1= - 500 lb ; FY_2= - 500 lb (@ lugs).

<u>Results</u>:
Maximum displacement equal to -0.354 E-3 inch, located at the cool mass attachment lugs.

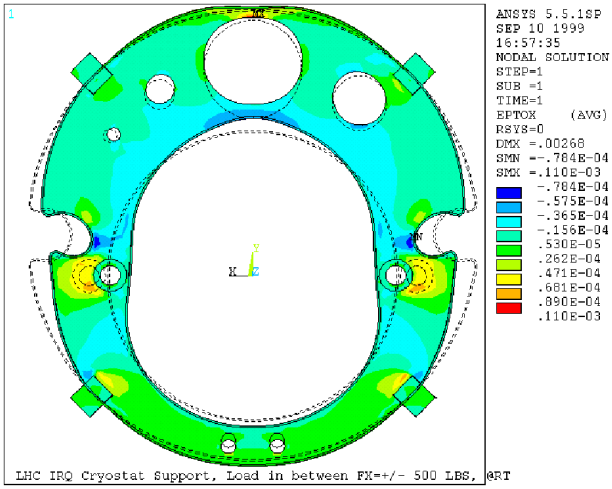

Figure 2: Example for a load applied inside the cold mass opening (pull along the X-axis) (simulation of the shrinking of the cold mass during cool down)

<u>Load</u>:
FX_1= - 500 lb ; FX_2= + 500 lb (@ lugs).

<u>Results</u>:
Maximum strain equal to 110 E-6, located at the cool mass attachment lugs.

The highest values of displacements and strains are located at the cool mass attachment lugs.
Table 1 summarizes the main displacements and strains calculated for the composite in the area of the lugs (location of the gauges SH and SG)(fig. 3b).

Parameter	***Vertical load***	***Load inside/ pull***	***Load inside/ push***	***Horizontal load***
Direction of the load	Y	X	X	X
Displacement (E-3 inch)	0.3	- 4.8	4.8	2.8
Strain (E-6)	54	116	- 136	68

Table 1: Numerical results for 1,000 lb force.

4 Experiment

4.1 Description of the test bench

The test arrangement has been re-designed on the basis of an existing set-up for testing of the SSC support post.
In order for it to fit the existing load frame, the support is fixed upside down (fig 3a). Its purpose is the measure displacements and strains at critical areas in the support.
The test bench enables us to fix the support at four steel reference bars (along the z-axis) and four lugs.
Forces are transmitted from the cylinder to the two pins by means of large steel bars bolted together.
Three positions of the cylinder are available in order to simulate a vertical load, a load applied between the lugs and a horizontal load.

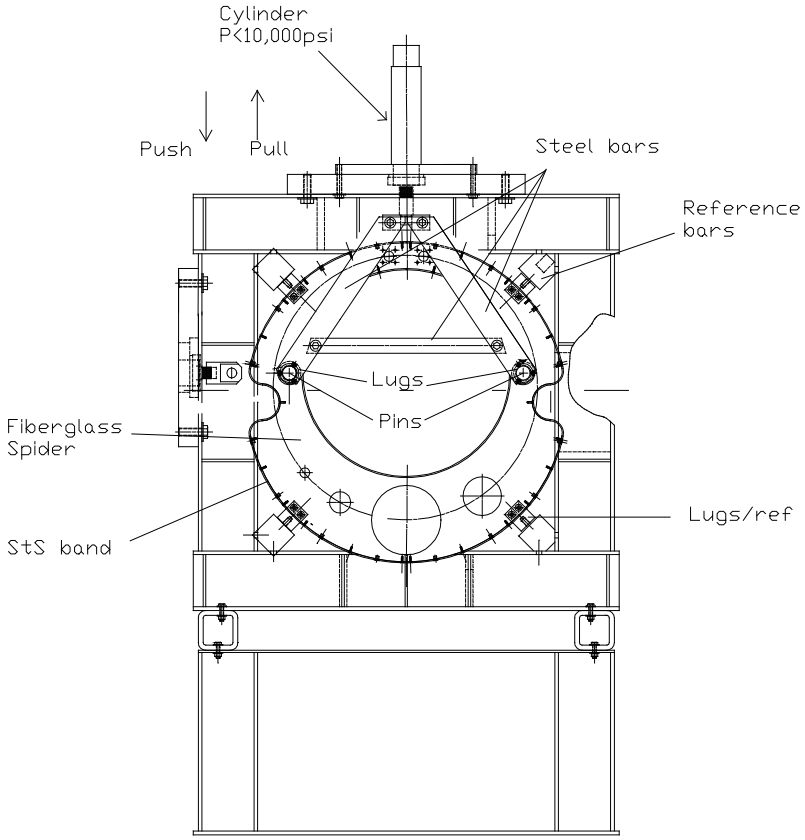

Figure 3a: Arrangement in the case of the vertical load applied at the two pins.

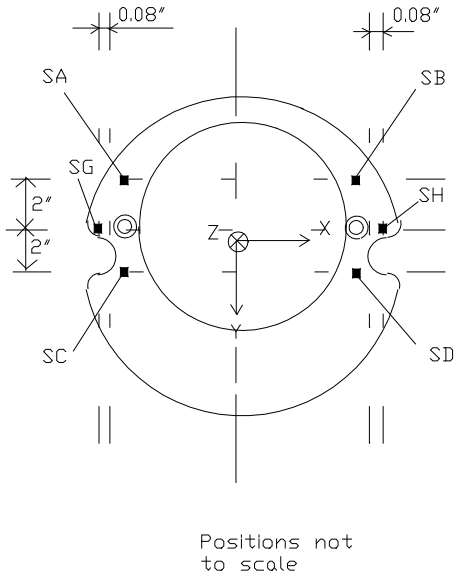

Figure 3b: Location of the strain gauges

4.2 Instrumentation

The cylinder can apply a force of up to 31,000 lb pushing and 15,000 lb pulling.
Six dial indicators measured the displacement of the pin, lugs and the composite plate, along X and Y-axis. They are fixed via magnets to the reference bars.
Sixteen strain gauges were required in order to complete the test and to crosscheck numerical results. Each physical gauge enables the measurement along X and Y-axis, via 8 electrical wires. Eight gauges are glued on the G11 plate as shown on figure 3b. The others are located in mirror position compared to the (X,Y) plane in order to check the symmetry of the applied load.
Strain gauges called SAY, SBY measured the strain along the Y direction. They are located 2 inches above each pin in an area where the strain is constant. SA2Y, SB2Y are their mirror gauges, located on the opposite side of the G-11 plate. SAX, SBX, SA2X, SB2X measure the strain in the X direction. SCY, SDY are located below the two pins. SC2Y, SD2Y are their mirror gauges. Strain gauges called SGY, SHY measure the strain right on the outside of each pin. SG2Y, SH2Y are their mirror gauges.
The acquisition of the strain measurement is possible via a program written in BASIC, which reads and stores data from 40 channels.

4.3 Results

In order to optimize measurements and to check their repeatability, the data is recorded using the following scenario:

- Strain gauges are trained up to a maximum load in order to calibrate the system.
- Three series of measurements are recorded by pulling from zero up to the upper load, increasing the load progressively.
- One more series for the repeatability of the measurement is recorded for the operational load only.
- A second set of data is recorded once the arrangement had been stressed in the opposite direction.

The same measurements had been performed by pushing up to the upper limit, for the three cylinder positions.

For the three cylinder positions, the main results are summarized in table 2. The following results are the experimental displacements and strains, at an applied force of 1,000 lb.

Parameter	*Vertical load*	*Load inside/pull*	*Load inside/push*	*Horizontal load*
Direction of analysis	Y	X	X	X
Displacement (E-3 inch)	1.1	- 15.5	15.5	6.5
Strain (E-6)	59	134	- 177	63

Table 2. Summary of the results

4.3.1 Vertical load

This force simulates the behavior of the support due to the weight of the cold mass. An operational force of 5,000 lb per pin is estimated in the case of the IRQ magnets. We applied a force up to 16,000 lb (pulling and pushing) in order to have a better amplitude for the measurement and in so far as the stress was much below the ultimate strength.

Figure 4 shows the strain in the Y-direction on gauges SA and SB as well as their mirror gauges SA2 and SB2.

Figure 5 shows the strain in the Y-direction on gauges SC and SD, located on the opposite side of the pins.

The thick line represents the finite element results.

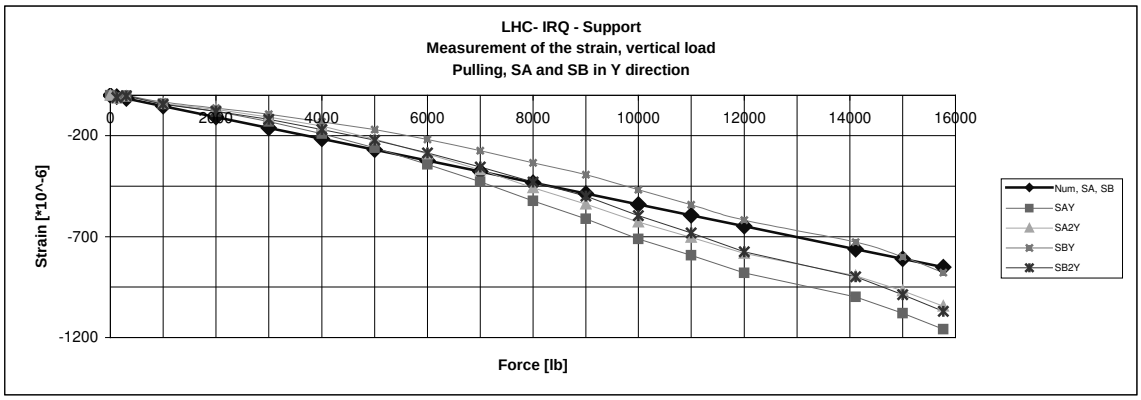

Figure 4: Strains due to the vertical load applied on the two support pins

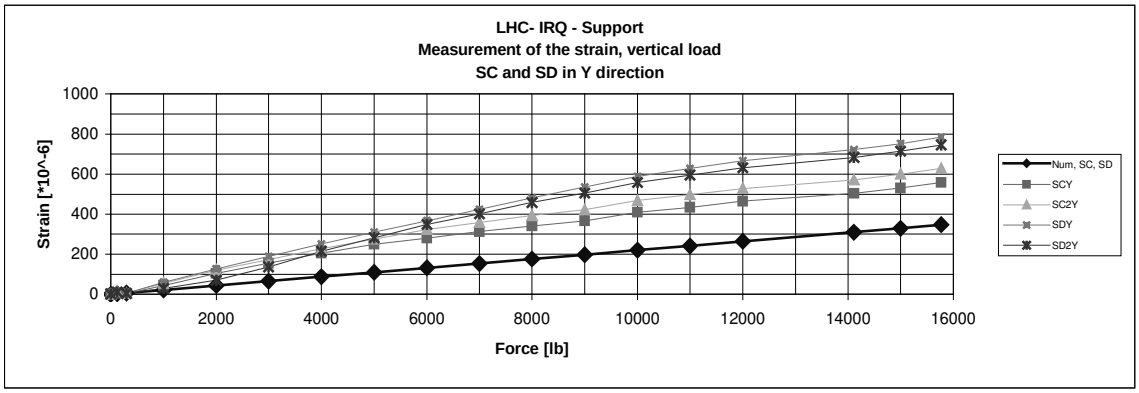

Figure 5: Strains due to the vertical load applied on the two support pins

4.3.2 Cool down load

Experimentally the cylinder is located in between the cold mass attachment lugs. The direction of the load simulates the force eventually applied during cool down of the cold mass.
The cold mass is known to shrink 0.040 inch on its diameter during the cool down. We decided to fix the operational range from the point of view of a maximum displacement of 0.040 inch on the radius. The corresponding load was 1,000 lb force. We pushed up to 2,000 lb, in order to simulate conditions during the shipment, then we pulled up to 2,000 lb in order to simulate the shrinking of the cold mass during the cool down. Figure 6 shows the strain registered for a +/- 1,000 lb pull in the X direction, figure 7 shows the strain while pushing in the X direction.

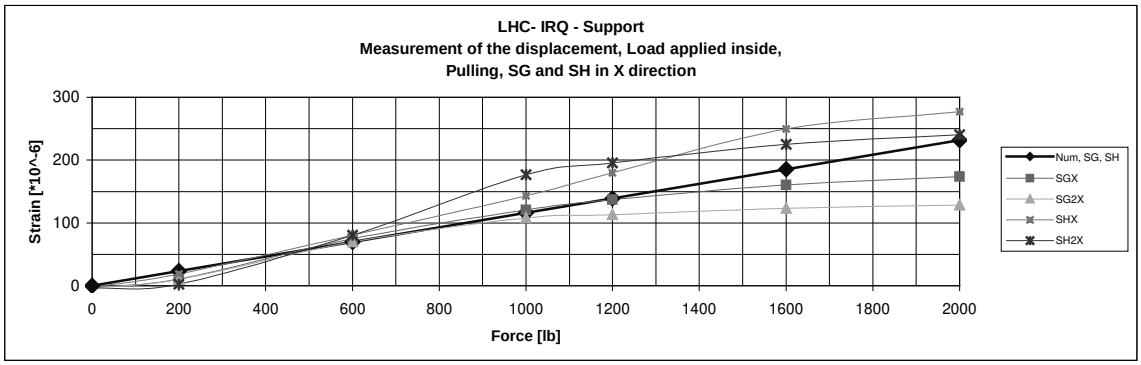

Figure 6: Strains due to the load applied between the cold mass lugs, pulling.

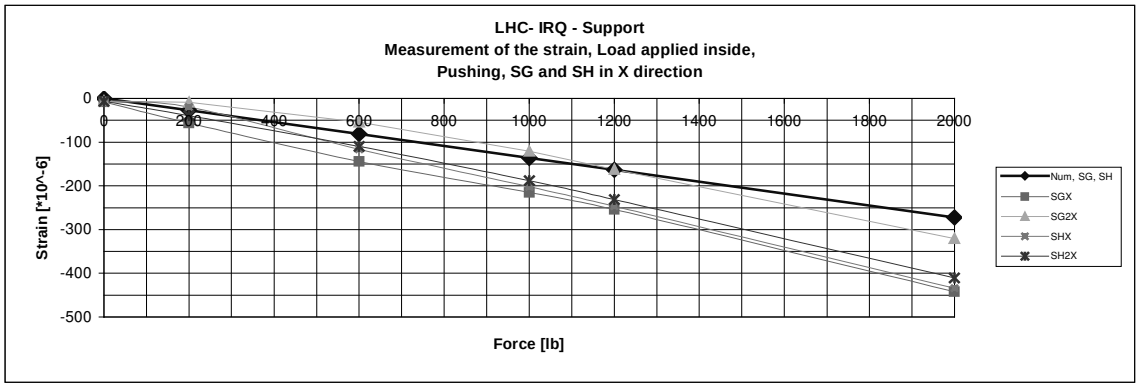

Figure 7: Strains due to the load applied between the cold mass lugs, pushing.

4.3.3 Horizontal load

The direction of the horizontal load simulates the force eventually applied during shipping and handling. We pulled and pushed up to 2,000 lb. Figure 8 shows the strain in the X-direction for four gauges located close to the pins.

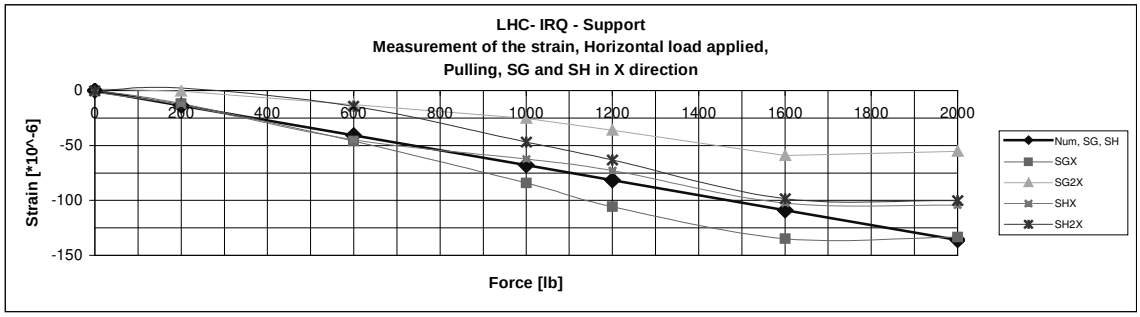

Figure 8: Strains due to the horizontal load.

4.3.4 Load to failure

In order to evaluate the upper limit of the support, we pushed the system with a cylinder installed horizontally. This position corresponds to the higher possible load/displacement for the system, and it can simulate an eventual condition during shipping.

The support broke when the force produced by the cylinder reached 5,860 psi (18,400 lb). The strain evolution had been recorded up to 17,270 lb. Figure 9 shows the strain of the two gauges located close to a pin, figure 10 shows the displacement of one lug in the X direction, compare to the numerical results.

Failure did not occur at the highest area of the stress indicated by the finite element model. The composite plate broke close attachment lugs. The area of the three screws (attachment of the lugs to the composite plate) was first subject to small cracks. Then the composite plate cracked on its thinner border.

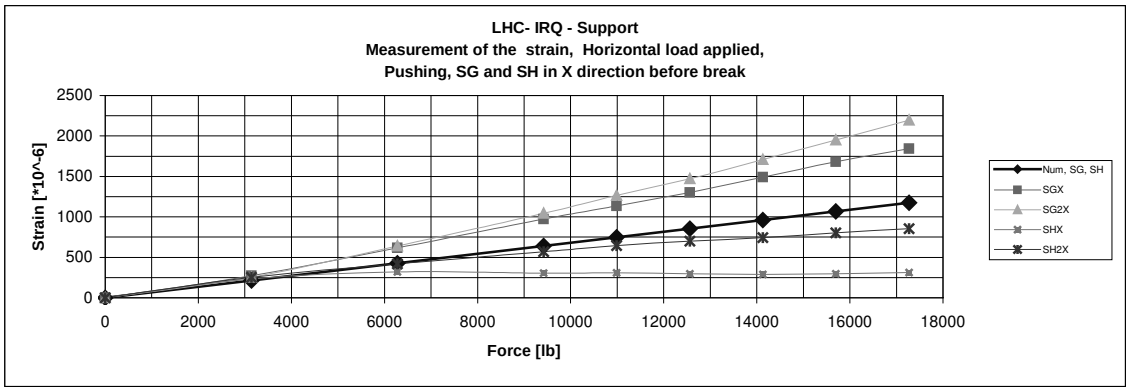

Figure 9: Strains due to the horizontal load before failure.

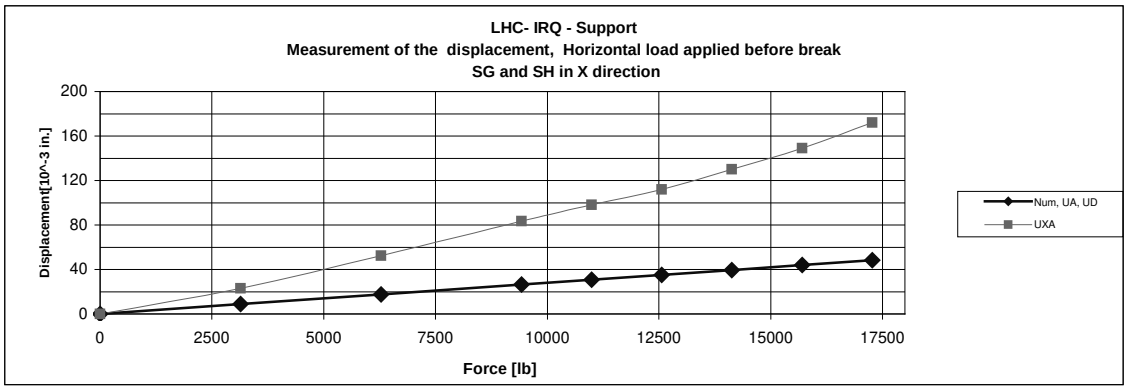

Figure 10: Displacement due to the horizontal load before failure.

5 Analysis and critique

The standard deviation and the error bar are calculated for every series of measurement, with gauges SA and SB in the case of the vertical load and with SG and SH for the other cases.

Displacements are much larger than expected. 0.172 inch had been measured instead of 0.048 inch calculated in the case of the rupture previously referred. If we consider each condition, strains are also larger than expected. Yet the distribution of the strain measured is large and a quite good agreement with the numerical model can be noticed.

Parameter	***Vertical load, pull, Y direction***		***Load inside, pull, X direction***		***Horizontal load, push, X direction***		***Horizontal load, push, X direction***	
Type	**Difference (%)**	**Std_dev**	**Difference (%)**	**Std_dev**	**Difference (%)**	**Std_dev**	**Difference (%)**	**Std_dev**
Displacement (E-3 in.)	72	0.4	69	0.5	69	0.6	57	0.5
Strain (E-6)	8	2.5	13	2.8	23	2.8	8	1.6

Table 3. Comparison between calculation and experimental results

If we compare for each arrangement, the strains and the displacements, we can notice that for the case of the load applied vertically, the strains are large and the displacements are small. For the case of the load applied inside and applied horizontally, the strains are small and the displacements are important. Thus the measurement of the displacement is really critical, due to the non-stiff set-up of the displacement gauges.

The standard deviation is relatively small for all measurements. The repeatability of the measurements is good.
The error between the numerical test and the measurements are acceptable considering the strain measurement. So, the numerical model can simulate reality regarding the strain measurements. But the displacements measured are much too large compared to those of the numerical model. Differences larger than 50 % can not reflect any reality. The displacement measurement set-up is very critical.
It comes out of the campaign results that the range used to apply the load was much too low, for the case of the horizontal load and load applied inside. We should have considered a range of 0-16,000 lb instead of 0-2,000 lb, in so far as figure 9 underlines a linear behavior up to such higher values.

For all cases, the strain had been registered from one side and the other of the composite plate. This information was really important to check the behavior of the support under load. We often took note that the support was twisted, due to a badly distributed force.

The large displacements measured can be due to many parameters. The arrangement as well as the numerical model does not consider the ideal case.
Concerning the experience, several criticisms can be given. By order of influence:

1. Gauges:
- Mechanical instability of the displacement gauges fixed by means of magnet, which do not constitute a rigid system.
- Location of displacement gauges out of the median plan, which creates a lever arm, consequently, a larger deflection.
- Strain gauges are glued on the G-11. The thickness of the epoxy layer can hardly be controlled and explain the distribution of the measurements.

2. Arrangement:
- The reference bars are supposed to be motionless. They are taken as reference even if 20,000 lb are applied on the system. Their motion is critical.
- The fixation between the support and the reference bar is assured by means of screws, which induce inadequate tightening and mechanical weakness compare to an ideal rigid assembly.

3. Forces:
- Force distribution and transmission can be unbalanced due to the long path of the stress on the system: cylinder/steel bar/lug/pin.
- The mechanical friction at the interface of the component can induce some unbalance forces on the support.

4. Support:
- The glass fiber composite is less rigid than expected.
- Orientation of the composite layout can be different than the requested 0/90 possibly, inducing a lower Young modulus in the direction of forces.
- Epoxy glass fiber can be subject to the time degradation.
- The connection between stainless steel slide and composite plate is done by means of screws located very close to the holes. The stresses are extremely high and the area is weakened.
- No glue was used to fix the stainless steel band and the composite, which induces less rigidity in the system.

Some important notes should be taken into account concerning the numerical analysis:
- The result value at the exact gauge locations is difficult to get.
- The meshing implies a full connection of nodes between the stainless steel elements and the composite elements, which means ideal connections between elements.
- The mechanical properties of all materials are as given in the literature but not based on measurements.
- All physical properties of the composite material are supposed to be isotropic and not orthotropic like in reality.
- The boundary conditions imply no displacement for the four external attachments of the model. In the experimental set-up, they are related to the reference bars.
- A perfect constant load is distributed on the suggested contact area, but not in the experimental set-up.

Some complementary data are available at the following web address: http://tspc01.fnal.gov/darve/support.html.

6 Conclusion

The measurement campaign provided interesting results considering the validation of the numerical model.
Nevertheless the measurement of the displacements is far from perfect and raise questions about the rigidity of the current composite material used for the test. The Young's modulus of the material will be measured with a dedicated test in order to check the value used for the numerical model. This test will consider various orientations of the fibers.
We ran a simplified set-up of to the real LHC IRQ support problem. We can still notice that no load along the Z-axis is considered for the support. In reality the pins have some friction, so extra load along the Z-axis should be taken into account. In order to measure this influence, a test will be dedicated to this friction phenomena.
The current results lead us to an improved support, which will be checked in a similar program. This support is under construction and the test is expected for October 1999. The future test should confirm the current theories.