Design of the Compact SRF Accelerator Assembly Stand

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I. Introduction

Industry has long needed the capabilities of a mobile accelerator which can produce a high energy electron beam. The Compact Superconducting Radio Frequency (SRF) Accelerator aims to bridge the gap between the needs of industrial applications and the research performed at Fermilab. The accelerator consists of several different components. The core of the accelerator is the cavity, which is surround by the thermal and magnetic shields. This subassembly is attached to the underside of the top plate. Until this subassembly is completed and lowered into the vacuum jacket, the top plate rests on a three sided structure that is shown in *Figure 1*. This structure is currently on loan to the lab, and will need to be replaced in the near future. Due to this, a new support structure is necessary to continue operations, which is the purpose of the Compact SRF Accelerator Assembly Stand (CAS).

Figure 1: Current Assembly Stand

II. Design Requirements

At most, the structure will need to support the top plate, a 4.5 cell SRF cavity, and several other components. The highest expected mass of this load is 725 kg. Per Fermilab standards [1], the minimum factor of safety (FOS) allowable will be 2.5. The plate will rest on top of the structure by its outer edge so that the instrumentation is not at risk of damage. Due to the length of the 4.5 cell cavity, the stand will need to be at least two meters tall, creating ample room for installation. For the benefit of those working on it, there will not be any cross members which may be an obstacle. As seen in *Figure 1*, there are cross members on the bottom of the stand. This presents a tripping hazard, and also makes it difficult to remove the cart which is needed for assembly work on the Compact SRF Accelerator. In order to reduce magnetic field interference, the stand should be built from a non-ferromagnetic material. Aluminum will be used since it is considerably less expensive than stainless steel, and the fabrication costs will be approximately the same. Lastly, neoprene sheets on the top surface of the stand will be required so that the polished or finished surface of the plate is not damaged when in contact with the stand.

III. Methodology

The first phase of this project was to understand the design requirements laid out in Section II above. After discussing them with the project supervisor, the next task was to design the CAS using Siemens NX, which is a 3D modelling program. This program is integrated with Fermilab's Teamcenter, which allows for shared use of all the model files and documentation. Once the initial design was completed, the geometry was imported to ANSYS for Finite Element Analysis (FEA). A static simulation was used since it is not expected that the load will change with time. At this stage, several discussions were held with experienced Mechanical Engineers on what conditions the simulation should contain, and what hand calculations need to be performed to determine the performance of the stand. These simulations and calculations are detailed in later sections.

After several minor design revisions and simulations, an Engineering Document was prepared. The purpose of this document is to have a detailed account of all the current results of the design. This document was presented to a review committee. This committee made further suggestions on conditions that the structure should be able to withstand. The suggestions were taken under consideration, and the stand was found to be suitable for all the scenarios presented. From here the CAS entered the procurement stage, and production began on site. The stand is currently scheduled for use in the Heavy Assembly Building (HAB) at Fermilab. After a ground survey to check for rebar and electrical conduit, it will be secured to the ground using one drop-in anchor per foot pad.

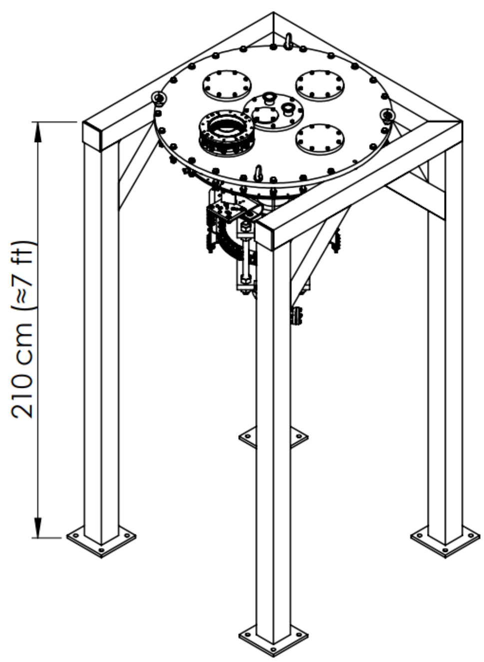

Figure 2 Isometric View of the CAS

IV. Calculations

The following is an overview of the calculations performed for the CAS. For a full analysis, please see reference [2].

A. Stability

P_{cr}: Critical Load at which buckling will occur (worst case)

$$P_{cr} = \frac{\pi^2 * E * I}{4 * l^2} \qquad [3]$$

E: Young's Modulus for 6061-T6 Aluminum = 68.9 GPa [4]

I: Moment Area of Inertia = 5E-6 m^4

L: Free length of the leg beam = 1.68 meters

P_{cr}= 303E3 Newtons (approx. 31,000 kg)

Expected load << Critical Load

B. Welding Shear

Due to the complex geometry involved with the angled supports, a simplified calculation was made to ensure the safety of the structure. The support of the angled beams was removed from this calculation, and the predicted weight was above what one would truly expect during operational use. Additionally, the upper members of the structure rest on top of the legs, and this induces less stress than if they were welded perpendicular to the legs, as seen in *Figure 3* below.

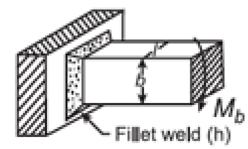

Figure 3 Welded Member Loading Conditions

σ_b: Maximum shear stress in weld material

$$\sigma_b = \frac{4.24 M_b}{h[b^2 + 3l(b+h)]} \qquad [5]$$

M_b: Moment applied to beam = 1500 N-m
(300 kg at a distance of .5 meters)

H: Weld leg length = .64 cm (1/4 inch)

B: Beam height = 10.16 cm (4 inches)

L: Beam width = 10.16 cm

σ_b = 23 MPa

F_y: Tensile yield strength of welded Material =105 MPa [6]

S_y: Shear strength: $S_y = 0.577*F_y$ = 60.6 MPa

Resultant Factor of Safety = 60.6/23 = 2.6

V. Simulation Conditions

FEA programs like ANSYS rely on the user specified conditions to create a solution. These conditions include how a component is allowed to move, what forces are applied to the system, and if contacts between components are frictional or if they are bonded (think welding) to one another. The more accurate these constraints on the system are to real life, the more the simulation can be relied upon as an accurate predictor for how the structure will respond to different scenarios.

For all of the following simulations, the location of the footpads was fixed, which is because the stand will be bolted to a concrete floor. Additionally, the only component of the Compact Accelerator in the simulation was the round stainless steel plate. This was important as it greatly reduced the number of components, which decreased computational requirements.

A. Static Simulation

Once disconnected from the vacuum jacket (not shown), the Compact SRF Accelerator is lifted by an overhead crane and then lowered onto the stand. Before making contact, bolts are positioned into the holes on the top plate and then aligned with the stand. This ensures that the subassembly will be in the proper location once it is fully resting on the stand.

Since the bolts are only acting as guide pins in this situation, there will be no pretension applied to them. There was a frictional contact between the plate and the stand, and there was a downward force applied to the top plate of 575 kgf. This is equivalent to the maximum expected load without the weight of the top plate.

B. *Seismic Simulation*

Even though significant seismic activity is rare at Fermilab, the stand must be able to endure this type of event. The building the stand it located in is rated to withstand short term shaking with accelerations of 22.5% of gravity or less. It is assumed that if an earthquake were to take place, it would be while the CAS is fully assembled, and the subassembly is securely bolted to the stand.

As in the static simulation, the same frictional contact between the top plate and the frame exists. These contacts had the appropriate static coefficient of friction, and three pretensioned bolts held the plate in place. Each bolt was modeled as one solid piece due to complications simulating individual washers, nut, and bolt. The tension applied to each bolt was 7 kN (approx. 1600 lbf). In addition to the weight of the static load, several forces were applied to the plate to simulate the forces caused by seismic activity. From the center of gravity of the load, 22.5% of the load's weight was applied in each the X, Y, and Z direction. Relative to the top plate, this created an additional downward force in the Z direction since it acted through the moment arm. In the X and Y directions, moments were created, and they were applied to the top plate.

C. *Other Simulations*

In addition to the aforementioned simulations, a few cases were requested by the design review committee to confirm the stands ability to withstand accidental impacts. Operator error, while rare, does still occur, and therefore it is a possibility that the stand could be hit by either a forklift or a crane hook. It is assumed that the forklift would only hit the stand if the operator were backing up towards it and made contact at a low speed. Forces equivalent to those that would be delivered by an average sized forklift were distributed across an area ½ a meter from the ground and 1/3 meter in height along one of the most vulnerable legs of the stand. This approximates the counterweight of a forklift, which is above ground level, coming into contact with one of the stand legs. The crane hook is most likely to hit one of the upper members of the stand. Forces equivalent to that impact were placed over a few square centimeters on one of the upper members.

VI. Simulation Results

A. *Static Simulation*

As seen in *Figure 4*, the maximum stress concentration in the structure is 23 megapascals (MPa). The tensile yield strength of the 6061-T6 Aluminum used is 276 MPa, which yields for a FOS of 12, which is much higher than required. Since the plate is not bolted down, and one side is open on the stand, most of the weight is distributed across the two upper parallel members. The highest point of stress is where the edge of the plate contacts the edge of the upper member, as one would expect.

It should be noted that when calculating the FOS, the effect of welding on the strength of the material was accounted for. The Heat Affected Zone (HAZ) of 6061-T6 has a much lower yield strength than non-HAZ aluminum at 105 MPa. At most, the distance from the weld that a HAZ occurs is one inch for thin metals [7]. The stress concentrated areas are approximately four inches away, and the welds experienced no significant stress in the static simulation, and so the tensile strength of non-HAZ 6061-T6 was used to determine the FOS.

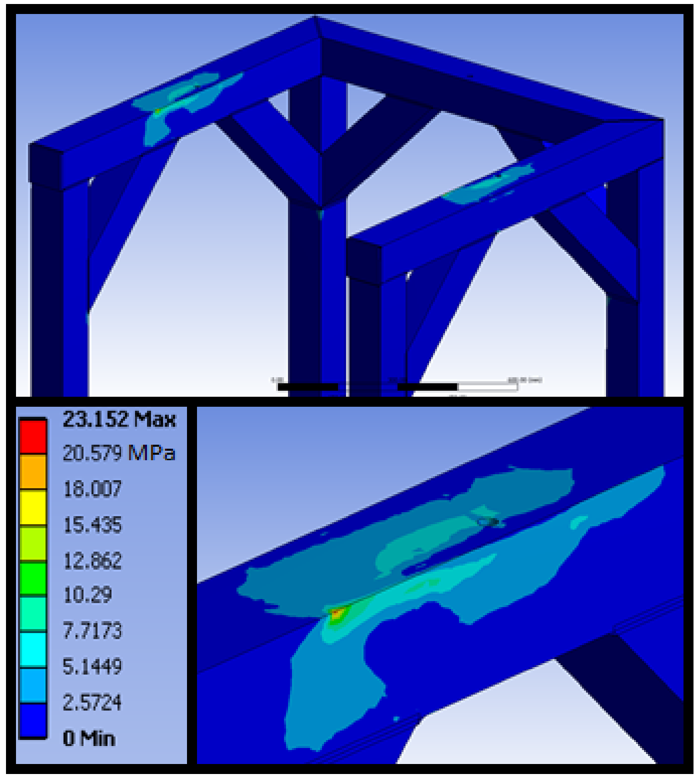

Figure 4 Top: Wide view of stress concentrations. Lower: Close up view of maximum stress

B. *Seismic Simulation*

As seen in *Figure 5*, the maximum stress concentration in the structure was 62 MPa. This yields a FOS of 4.5, which is still higher than required. The highest stress in the bolts (not shown) were 102 MPa, and with a yield strength of 482 MPa yields a FOS of 4.7. There are noticeable differences in the distribution of stress when comparing Figures 4 and 5 and this is largely due to the pretensioned bolts which are present in the seismic simulation. The tensioned bolts help to evenly distribute pressure across the upper members, and create some additional stress within the beams. The highest point of stress in the aluminum structure is on the underside of the upper beams on the edge of the bolt hole. This is expected since the holes cause for an irregularity in the geometry, and a considerable amount of force is being applied at this location.

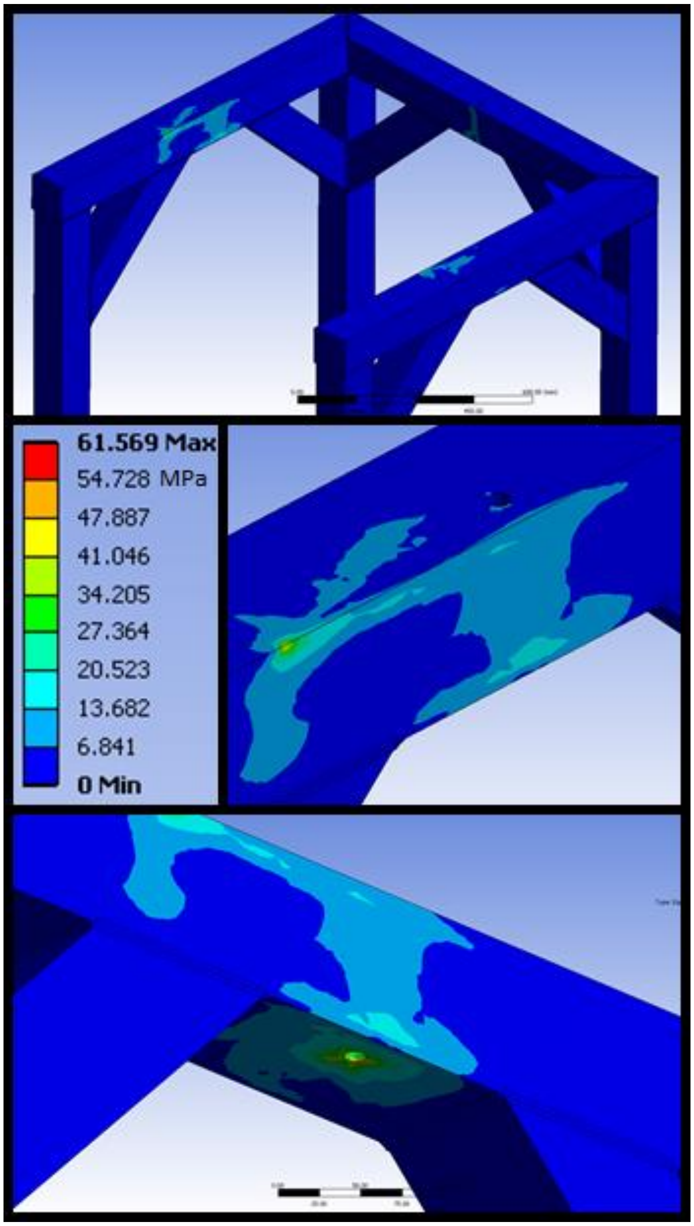

Figure 5 Top: Wide view of stress concentrations. Middle Left: Scale, Unit MPa. Middle Right: Close up from above. Bottom: Close up from below

It should be noted that additional seismic forces only cause a five percent increase in stress compared to just a static structure with pretensioned bolts. Before the additional load and moments were applied, the stress at the point where the plate edge meets the upper member edge was considerably less, and the stress overall was evenly distributed.

C. *Other Simulations*

The results from the additional cases were acceptable. It was found that no damage to the structure would occur from an impact from either the crane hook or forklift. The largest concern remains that the forklift has the potential to shear one bolt connecting the stand to the ground if it is moving at a speed above 10 cm/s, and the operator makes no attempt to stop their motion.

VII. Conclusion

The Compact SRF Accelerator Stand is a valuable addition to the goal of merging Fermilab's technology with industrial applications. Finite element analysis showed that in worst case scenarios, the structure will still have high factors of safety, and the overall design was approved by the review committee.

As of now, the CAS has been completely assembled and is located in the Heavy Assembly Building at Fermilab, as shown in *Figure 6*. Load testing of the stand is most likely not necessary due to the high factors of safety engineered into it. However, if it were performed, it would be to a test load of 900 kg, and would require the top plate and pretensioned bolts to be used so that the conditions are similar to those intended.

Figure 6 Current state of the CAS

Acknowledgments

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