|  |  |
| --- | --- |
| Image result for DUNE LOGO | **Structural Design Safety Validation** |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Title: DUNE APA Structural Analysis Validation | | | | | | | | | | | | | | | | |
| Author(s): Farshid Feyzi | | | | | | | Approved: Management | | | | | | | | Page: 1 of 1 | |
| Document ID: EDMS 2142671 | | | | | | Version: 0 | | | | | Version Date: 18 Apr 2019 | | | | | |
| **REVISION HISTORY** | | | | | | | | | | | | | | | | |
| **Version** | **Description of Change** | | | | | | | **Author** | | | | | **Effective Date** | | | |
| 0 | Initial Release | | | | | | | Farshid Feyzi | | | | | 18 Apr 2019 | | | |
| **Installation, equipment or project:**  DUNE Anode Panel Assemblies | | | | | | | | **Technical supervisor:**  Alberto Marchionni | | | | | | | | |
| **Department or group:**  APA Consortium | | | | | | | | **Location:**  FNAL | | | | | | | | |
| **List of documents submitted for validation:** | | | | | | | | | | | | | | | | |
| **Type** | | **Identification** | | | | | | | | **EDMS** | | | | | | **Date** |
| Report | | DUNE APA Structural Analysis Master Report 2019 | | | | | | | | 2100877 | | | | | | 26 Feb 2019 |
| Drawings | | Frame Drawings | | | | | | | | 2100877 | | | | | | 26 Feb 2019 |
| Report | | DUNE APA Structural Analysis Master 2019v3 | | | | | | | | 2100877 | | | | | | 26 Mar 2019 |
|  | |  | | | | | | | |  | | | | | |  |
| **SAFETY DOMAINS** | | | | | | | | | | | | | | | | |
| Biological  Chemical  Cryogenic  Electrical and electromagnetic  Emergency | | | | Environment  Ergonomics  Fire  Mechanical  Non-ionizing radiation | | | | | | | Radiation protection  Structural  Workplace  Worksite  Other (Specify) | | | | | |
| **REFERENCE DOCUMENTS** | | | | | | | | | | | | | | | | |
| **Document ID Number/URL** | | | **Document Title** | | | | | | | | | | | | | |
| Plan | | | APA Analysis Plan v6 | | | | | | | | | | | | | |
|  | | |  | | | | | | | | | | | | | |
|  | | |  | | | | | | | | | | | | | |
| **Comments** | | | | | | | | | **Person** | | | | | **Date** | | |
| Questions and answers- Appendix 1 | | | | | | | | | SCWG | | | | | 8 Mar 2019 | | |
| Comments during APA 60% design review- Appendix 2 | | | | | | | | | SCWG | | | | | 28 Mar 2019 | | |
| Outstanding issues- Appendix 3 | | | | | | | | | SCWG | | | | | 28 Mar 2019 | | |
| Outstanding issues do not affect structural analysis to a substantial degree. They need to be corrected by May 31, 2019 and report resubmitted. Structural analysis is accepted at the 60% design level. | | | | | | | | | SCWG | | | | | 26 Apr 2019 | | |
| **CONCLUSION** | | | | | | | | | | | | | | | | |
| Immediate Correction | | | | Correction with deadline | | | | | | | Validated | | | | | |
| Prepared by: Farshid Feyzi | | | | | Date: 18 April 2019 | | | | | | | EDMS: 2100877 | | | | |
| Safety officer(s): Michael Andrews | | | | | | | | | | | | | | | | |

**APPENDIX 1**

**Questions**

**on**

**DUNE APA Structural Analysis**

**by**

B. Wands, O. Beltramello, M. Zhao, J. Hrivnak, F. Feyzi

March 8, 2019

The analysis of the APA frame and associated components is very thorough and is on track with the design review at this stage. Following comments and questions are provided in order to improve the analysis and documentation.

Verification of the analysis utilizing a different FEA code and as documented in appendix 3 is a very good and important step taken by the group. It should be done with all similarly critical DUNE systems.

General Comments:

1. The APA is substantially the same as the ProtoDUNE APA with some differences: frame size, wire tension, others? Explain this, in the introduction.

Similarities and differences between DUNE and protoDUNE will be added to the introduction.

1. AISC 360-10 was used in the analysis, while AISC 360-16 is the current edition, have you verified if the analysis conforms to the current edition?

ProtoDUNE was done using ASD which, I believe, isn’t included in 360-16. We were extending this to DUNE. When the decision was made to switch to LRFD we stayed with 360-10 out of familiarity. We have not looked at the current edition yet.

ProtoDUNE frames were analyzed in a similar manner and they worked very well. Reference to that work should be made in this report.

Reference to the protoDUNE analysis will be added.

1. In ProtoDUNE, endwalls were supported on APA and CPA, In DUNE we do not plan to do this and we leave the endwalls supported on DSS. Need to verify this with HV group.

In protoDUNE the endwalls were delivered to their final position while being supported on an extra bridge beam. The load of the endwalls was then transferred to the APA and CPA beams that were part of the DSS. The endwalls were not supported on the APA or the CPA.

1. Would be possible to see CAD model of the APA inside the transportation frame?

Yes. This will be added.

1. We need to do a general FEA model of the TPC with CS, DSS and HV in order to verify that the full detector meets physics requirements. To this end we will need an ANSYS model of an APA stack. This should be prepared.

We will prepare an ANSYS model of the APA stack for this analysis.

1. All documentation, drawings and 3D models should be put on EDMS and released for the review.

All documentation will be uploaded to EDMS for the Review. Since this is a 60% review, the drawings will not be released for production.

1. In mass estimation has included uncertainty for each component. Have you taken into account the experience from mass as designed and as installed from ProtoDUNE?

We have not compared the protoDUNE design mass to actual. If an accurate mass of APA 7 can be determined, this check will be done.

1. Include relevant parameters as an appendix for information: number of wires, wire material and diameter, wall thicknesses, tube sizes, bolt sizes and grades, weld material and grade. etc.

Will do.

Specific Questions and Comments:

1. Figure 2 does not show very clearly the scope of exactly what this analysis covers. Show a graphical representation of the APA doublet and associated components that are in the scope of this review, e.g. yoke, link, connections to fieldcage, etc.

This will be added.

1. In the summary table 1, add the factor by which weld and beam stresses exceed the allowable values. Add case 19 to summary table.

This will be added.

1. The interface between upper and lower APA are not shown. Is the link the only interface?

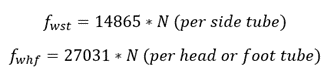
There are also pins planned in this interface. This will be explained and illustrated.

1. The link between the 2 APA is made from fiber reinforced polymer, G10. The analysis of the link is done per AISC code. A design standard applicable for FRP should be used.

We will investigate using the 2016 EU JCR document “Prospect for New Guidance in the

Design of FRP”

1. The wire load is the most substantial load on the frames. Bu it is not shown how it is calculated. In following, what is \* between the number and N? Where do 14865 and 27031 come from?



The derivation of the wire load will be added. Wire tensions have 1.4 load factor. Explain this.

1. In FEA of case 1, are the two edge lift kits included in the FEA model? If yes, explain how he boundary conditions applied. It is not very clear from the description of the constraints.

A better explanation will be added

1. In Figure 27, how are the Y and Z direction shears from Mx calculated?

A better explanation will be added.

1. According to the AISC Specification for Structural Steel Buildings, (the Specification) the strength of the base metal in a fillet welded joint is governed by Part J4, which states “The available shear strength of affected and connecting elements in shear shall be the lower value obtained according to the limit states of shear yielding and shear rupture.” Referring to Figure 29 of the report, the available base metal strength for rupture and yield were calculated, but the available rupture strength was chosen over the available yield strength even though the available yield strength was smaller. Can this choice be justified?

I am checking the base metal available strength. I think the available will not be as low as the value shown in the calculation because the correct values use higher resistance factors.

1. The available strength of the base metal is calculated using the full wall thickness of the SS tube. This is sensible for the case where a plate of a given thickness is fillet welded with a weld leg equal to that plate thickness. However, there is no width of fusion greater than 1.5 mm anywhere in the actual joint. Should the available strength of the base metal be based on the maximum fusion of 1.5 mm?

From more detailed explanations available on the web, the base metal strength appears to refer to the actual strength of the members near the weld – not the area where the weld contacts the base metal as one might expect.

I suspect the reason is that that region has a cold working ultimate strength similar to the weld metal. Their main concerns would be rupture of the weld and yielding of the adjacent member.

1. Choosing the available base metal strength based on yield, and using 1.5 mm instead of the full wall thickness, gives an available strength of 1.02e5 N/m, which is less than the fillet weld throat available strength of 1.82e5. Would this change any conclusions?

If we determine that using 1.5mm and yield strength is the correct approach we will look at the effect of the lower available strength.

1. In the Specification, the factor Φ is given as 0.9 for yield-based failure, and 0.75 for rupture-based failure. Can the choice of 0.55 for both criteria be explained by the requirements of stainless steel design (Design Guide 27)?

I believe the 0.9 and 0.75 factors apply to member strength. Section 9.2 of Design Guide 27 seems to be saying that, with austenitic stainless steels, 0.55 should be used on the strength of the weld material itself.

1. Please state the property class of the M10 and M12 bolts, their relevant properties, and present the calculation for the nominal and available strengths. (This is analogous to what was already done with the welds in Fig. 29)

Will add property class.

1. From the Specification, Part J3-7, “Combined Tension and Shear in Bearing-Type Connections” accounts for reduction in tensile capacity of a bolt that is under shear. Should this part be applied to the APA bolting analysis?

Based on the note in Part J3-7 the combined stress need not be investigated if less than 30% of the available is used. Where this is not the case the combined stress will be checked.

1. Please create a table with one line per joint, and columns that give the highest ratios of required/available strengths for the welds and bolts, as well as the load case(s) for which these occur.

This will be added.

1. In Appendix 2:

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Mass Label** | **Mass Description** | **Support Location** | **Type of Load** | **Mass/ APA (kg)** | **Contin- gency %** | **Mass Total (kg)** | **Mass with Load Factor (kg)** |
| m46 | CE cables and tray top |  | point | 55.0 | 10 | 60.5 | 84.7 |
| m47 | FC latches top |  | point | 12.0 | 10 | 13.2 | 18.5 |

In the APA Yoke Analysis,

M46 divided by 4 is not 4.6. Is this an error?

This mass reference should have been m47 which is 18.5kg or 4.6kg per point. This will be corrected.

1. The summation of the reaction forces and comparison to mass times gravitational acceleration as shown in appendix 9 is a very important verification step. But there are minor differences of about 1% . Explain why this is the case.

This will be investigated.

1. Distributed load on APA is explained but numbers are in units of mass. What does this mean? If it is a load it is a force, a force per unit length, or per unit area and is independent of direction of gravity. If it is a mass then gravity determines the direction of load. Please explain. Page 46 explains this further. But still does not explain how distributed loads in Kg are applied as pressure and how they are then applied in the direction of gravity. Pressure is always normal to the surface.

These “loads” represent the masses that are attached to the frame like wire board masses. It would be more appropriate to call them distributed masses. The direction of gravity changes depending on the case and the acceleration of gravity is applied in the appropriate direction in the FEA model. The load in the FEA model is applied as a load per unit area. This will be explained more clearly.

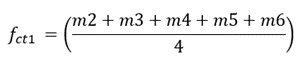
1. The formulas for load (or mass) distribution are complex. Please explain the method in simpler terms.

The distributed mass is different for different cases and applying properly is somewhat complex. An effort will be made to explain in simpler terms.

1. On page 23 and 24, in the following, shouldn’t the numerators be 6.2 and 2.3? Should the 6 in denominator be 6.3?


The numerator 2.3 (not 2) is correct and was used in the load calculations to assign the masses to the perimeter of the APA. The numerator 6 was used in the load calculations rather than 6.2. The total mass is still correct. The distribution is slightly off. The effect of this will be evaluated and a decision made on how to address in the report.

1. In the following, shouldn’t the denominator be 2?  
     
   

This mass is distributed on 2 side tubes and 2 surfaces of the center tube. This will be better explained.

1. On page 28, what is shown in figure 8, solid support bars, cable conduits or something else?

This image will be clarified

1. On page 31, in figures, such as 11, parts of figure are shown in different orientations. Axes are used to help clarify. But it is still very confusing.

Images will be changes so gravity is always acting “down”.

1. Case 19, the temperature gradient is very conservative which essentially assumes there is no thermal conductivity in the frame. And as shown in the analysis it generates very high stresses in the weld. Page 21 states: “ During the cool down, the APA may be subjected to a vertical thermal gradient, so the amount of thermal gradient that the APA can tolerate will be estimated by FEA analysis.” Is case 19 meant to place a limit on thermal gradient. A better analysis of gradient as expected in DUNE is required in order that a more realistic analysis of the frame can be done.

An error was made in the reporting of the forces acting on the joints that resulted in stresses for this thermal cases being 4 times higher than actual. The temperature gradient actually has very little effect on the stresses in the frame. These results will be corrected.

1. In regard to the finite element model:

* Include a sub-model of slot regions in side tubes.

Analysis of the effect of the PD insertion slots and the PD cable slots will be added.

* Element sides of up to 200 mm, is that correct? Seems too large when wall thickness is 3 mm.

Aspect ratio controls limit the length of element sides to significantly lower values in the actual mesh. The appropriateness of the actual mesh size will be investigated.

* Are filet welds actually in the model as fillets? Show this in a figure.

The details of the actual welds will be provided.

* Show a typical element plot.

This will be added

* Tetrahedral elements in the ANSYS simulation might lock the model in bending (LOCKING - phenomenon during bending- the solid element will show the bending behavior much stiffer in comparison with analytical solution.) and make stress reading inaccurate. Have you considered using shell element instead.

The APA is constructed of tubes and plates. The plates are best modeled as solids and do not mesh well with shell elements. It is not believed that there is an issue with the elements locking the model, but a better explanation will be provided.

1. Consider lateral-torsional buckling due to unbalanced forces acting on the yoke. What is the SF? Was load factor used?

The analysis was done using the first three modes of buckling. The plotted results are from the mode least resistant to buckling.

1. Wires will get cold much sooner than stainless frame because the wires thermal mass is much lower than in case of the frame, which will results in an increase in tension in wires and thus increase of the load on the frame. Consider adding an additional load case with increased forces (pretension + forces induced thermally) acting on the frame and use it to assess the buckling and stresses.

This analysis is in progress.

1. Bottom APA will get colder before Top APA which would lead into bottom APA shrinking more than the top one. This will result in bending of the APA-to-APA link. To support the load case relevancy, bottom APA will be immersed in liquid argon first, and heat between APAs will be transferred via conduction. Taking into account than G10 is a thermal insulator, and the link is connected with the APA using pin connection, will create sizeable thermal resistance. All of this mentioned above would create a steep temperature gradient between two APA which will lead into different shrinkage and in order to accommodate the thermally induced deformations, APA to APA link will experience bending.

The effect of the bottom APA shrinking faster that the top will be investigated.

1. Add a discussion of the relative effects of self-weight and wire tension on stresses.

APPENDIX 2

The applicable codes (ANSI/AISC 360-10, Design Guide 27, and the JRC Science for Policy Report “Prospect for New Guidance in Design of FRP”) have been properly applied to the engineering analysis

The engineering analysis examines 20 loading conditions, covering the critical phases of APA handling. Where details are not yet known (e.g., handling in the underground ITF facility) conservative assumptions have been made in the interim.

The engineering analysis is far more thorough than that of the protoDUNE experiment. This fact could be mentioned in the report

Weld integrity is critical in the APA frame. Welding will be done by certified welders and appropriately inspected.

Buckling analyses were appropriately performed on the frame and yoke and demonstrate substantial margins against instability

The transient thermal analysis shows that the temperature difference between the wires and the frame cannot exceed 75K if cooldown is slower than 3 hours

The resistance factor (0.55, taken from Design Guide 27) applied in the base metal available strength calculation is likely incorrect. The 0.55 should apply only to the weld metal. The standard steel resistance factors should apply to the base metal. However, these factors are higher, and using 0.55 is actually conservative.

The differential thermal contraction analysis of the G10 links might better be approached from the standpoint of a tip-guided cantilever beam, and bending stresses in the net section at the pin hole might be a better measure of adequacy. However, the links are far from marginal in this regard, given their length, low modulus, and relatively small displacement. No conclusions would be changed.

The report is overlong, and somewhat tedious to follow. It also lacks some detail. For example, the description of FE model loading for load case 20 is vague, and doesn’t mention that this is a transient analysis. The presentation, to the contrary, was crisp and accessible, and made clear some details that weren’t clear in the report.

The analysis is more comprehensive than was done for ProtoDUNE. More load cases, including transportation and thermal cases were studied. The calculation of maximum acceleration load is a good way to derive requirements for shipping containers and methods.

Using LRFD method, instead of ASD method that was done for ProtoDUNE is more advantageous as it conforms to latest revision of AISC and Eurocodes.

Rigorous analysis of all welded joint was done using AISC code. Welds were also represented correctly in the FEA model and stress results were used as reference for weld calculations.

The analysis per AISC codes shows that the frames meet the code requirements while not overly designed. This is advantageous from a performance point of view by minimizing mass of the frame.

Detail analysis of the regions with slots for PDs and PD cables was done using sub-models. This is an improvement over ProtoDUNE analysis.

The analysis was verified independently by Bob Wand using the model and load cases but employing different FEA software. This method of verification is very robust and should be followed in other parts of the detector.

The thermal analysis uses very conservative assumptions for temperature distribution in the frame. While the stresses are still within code requirements whit such conservative assumptions, work should continue to improve the models including a more realistic temperature distribution

The PD slots were removed from the frame to reduce analysis time. Load case 9 with the 4g load was rerun with slots. Worst load case presenting high stresses at other areas is not necessarily the worst load case where slots and holes see high stresses. Justification is needed to explain the load case 9 is the worst load case for slots and holes.

APPENDIX 3

* The thermal analysis uses very conservative assumptions for temperature distribution in the frame. While the stresses are still within code requirements with such conservative assumptions, work should continue to improve the models including a more realistic temperature distribution
* The PD slots were removed from the frame to reduce analysis time. Load case 9 with the 4g load was rerun with slots. Worst load case presenting high stresses at other areas is not necessarily the worst load case where slots and holes see high stresses. Justification is needed to explain the load case 9 is the worst load case for slots and holes.
* The resistance factor (0.55, taken from Design Guide 27) applied in the base metal available strength calculation is likely incorrect. The 0.55 should apply only to the weld metal. The standard steel resistance factors should apply to the base metal. However, these factors are higher, and using 0.55 is actually conservative.
* The differential thermal contraction analysis of the G10 links might better be approached from the standpoint of a tip-guided cantilever beam, and bending stresses in the net section at the pin hole might be a better measure of adequacy. However, the links are far from marginal in this regard, given their length, low modulus, and relatively small displacement. No conclusions would be changed.
* The report is overlong, and somewhat tedious to follow. It also lacks some detail. For example, the description of FE model loading for load case 20 is vague, and doesn’t mention that this is a transient analysis. The presentation, to the contrary, was crisp and accessible, and made clear some details that weren’t clear in the report.