Mechanical Safety Subcommittee Guidelines for Design of Vacuum Vessels using ASME Design by Analysis Methods

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# 1.0 INTRODUCTION

Fermilab uses the design rules of ASME Boiler and Pressure Vessel Code Section VIII for designing vacuum vessels. The design by analysis (FEA) methods are covered within Division 2, Part 5 of Section VIII. FESHM lists Div. 2 parts 5.2 (Protection Against Plastic Collapse), and 5.4 (Protection from Buckling) as applicable sections regarding vacuum vessel design. Through Parametric Analyses, it was found that one could design a vacuum vessel which satisfies code requirements of Div. 2 Parts 5.2 and 5.4, but fails when put into service. This document describes those types of failures, explains how to properly analyze them using methods described in the Code, and provides recommended factors of safety to be used in the design process.

# 2.0 TYPE OF FAILURES MISSED BY ASME PARTS 5.2 AND 5.4

Div. 2, Part 5.2 is used for protection from plastic collapse, without consideration of buckling. Div. 2 Part 5.4 solves for buckling without consideration of plastic failure. It has been found that a vacuum vessel may have a failure mode which is a combination of soft buckling and plastic failure which greatly reduces the actual strength of the vessel compared to the strengths predicted by the plastic failure analyses and buckling failure analyses individually.

Vessels which show any plasticity at design load, and a linear elastic buckling safety factor lower than 6 should be analyzed for true failure by the methods listed in this document, which follows the methods listed in Div. 2 Part 5.2.4 and 5.4.1.2(c) Type 3, with some minor changes/clarifications.

# 3.0 FAILURES ANALYZED WHICH SHOWED REDUCED STRENGTH

An obround Vacuum Vessel with stiffeners was analyzed using Div. 2 Part 5.2.3 Limit Load Analysis method, which met the required 1.5x load factor required by code. Buckling analysis were then performed using all 3 methods listed in Div. 2 Part 5.4 (type 3 using elastic material properties as allowed by code) with all three surpassing the required buckling safety factor. Results showed safety factors for Type 1, 2, and 3 analysis to be 3.31, 1.98, and 2.65 respectively. The true safety factor for this vessel was found to be 0.97, under 1.0, meaning it would fail the first time it was put into service. Details on the geometry and analyses are shown on slides 18 and 20 in section 6.0 of this document. This same type of failure could be seen in slightly out of round cylinders with stiffeners, as well as rectangular vessels, and possibly other shapes as well.

# 4.0 ANAYSIS METHOD TO FIND TRUE STRENGTH

For the analysis method to accurately predict true failure, we must consider both the non-linearity of the material, as well as the non-linearity in the geometry, in the same analysis. Div. 2, Part 5.2.4 describes this method, which should be used with minor guidelines/clarification listed here:

**Non-linear Material Properties:**

True Stress Strain curve from Div. 2 ANNEX 3-D.3 should be used for the material. While Elastic Perfectly Plastic is a conservative material vs true stress when the material is in tension, it is not conservative when buckling is a factor. This is because the tangent modulus starts decreasing after the proportional limit, which is before yield stress. Buckling strength is based on Young’s modulus, or in this case, the tangent modulus.

Tables for two types of Stainless Steel has been provided in Section 5 of this document. The data contained would be used as property data for “Multilinear Isotropic Hardening.” These properties are based on the Code listed Yield and Ultimate strengths for the material used in the design. Tables for other materials can be developed using the methods described in ANNEX 3-D.

**Non-linear Geometry:**

The effects of deformation and the stress and behavior on the deformed shape are of great importance. We must use large displacement theory, not small displacement theory, as is used in the Limit Load Analysis method.

**Symmetry NOT used: See ASME Section VIII-Div. 2 Paragraph 5.4.2**

Symmetry must not be used if it will result in the exclusion of a critical buckling mode. While some symmetry may be employed, it should be carefully determined that it will not exclude a critical buckling mode.

**Required Safety Factor using this method: 1.5**

The recommended load factor for this analysis shall be 1.5 at a minimum. The load should be gradually increased until a minimum of 1.5x the design load is applied, and the numerical model converges, showing structural stability at that load. The gradual increase in load should be used as to not jump over bifurcation points in the solution.

**ASME Parts 5.2, 5.3, and 5.4 shall still be used and requirements satisfied.**

This analysis shall be performed in additional to the standard ASME Design by Analysis methods listed in section Div.2 Parts 5.2, 5.3, and 5.4. It is not meant as a replacement, but rather an additional requirement for vacuum vessels which show plasticity and are subject to having failure modes missed by the Div. 2 Part 5 analyses.

# 5.0 MATERIAL PROPERTY TABLES FOR TWO TYPES OF STAINLESS STEEL

TABLE 1: This table was developed only for Stainless Steel with a code listed Yield Stress of 30 ksi, and an ultimate strength of 75 ksi. These values are inputs to the equations in Annex 3-D.3. The table starts with zero plastic strain at the proportional limit, and extends to the True Ultimate Stress, which is higher than the Engineering Ultimate Stress of 75 ksi.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stainless Steel with Sy/Su = 30/75 ksi** | | | **Table for Input into Property data for Multilinear Isotropic Hardening** | | | | | | | |
| **Plastic Strain** | **Stress** |  | **Plastic Strain** | **Stress** |  | **Plastic Strain** | **Stress** |
| Young's Modulus | 28000 | ksi | **(m/m)** | **(psi)** |  | **(m/m)** | **(psi)** |  | **(m/m)** | **(psi)** |
| Poisson's Ratio | 0.31 |  | 0.00 | 11977 |  | 5.2223E-02 | 47552 |  | 2.0805E-01 | 83127 |
|  |  |  | 1.0840E-05 | 13055 |  | 5.7089E-02 | 48630 |  | 2.1409E-01 | 84205 |
|  |  |  | 2.5965E-05 | 14133 |  | 6.1714E-02 | 49708 |  | 2.2023E-01 | 85283 |
|  |  |  | 4.6556E-05 | 15211 |  | 6.6122E-02 | 50786 |  | 2.2646E-01 | 86361 |
|  |  |  | 7.4009E-05 | 16289 |  | 7.0353E-02 | 51864 |  | 2.3280E-01 | 87439 |
|  |  |  | 1.0996E-04 | 17367 |  | 7.4453E-02 | 52942 |  | 2.3922E-01 | 88517 |
|  |  |  | 1.5632E-04 | 18445 |  | 7.8467E-02 | 54020 |  | 2.4575E-01 | 89595 |
|  |  |  | 2.1533E-04 | 19523 |  | 8.2433E-02 | 55098 |  | 2.5236E-01 | 90673 |
|  |  |  | 2.8961E-04 | 20601 |  | 8.6384E-02 | 56176 |  | 2.5908E-01 | 91751 |
|  |  |  | 3.8224E-04 | 21679 |  | 9.0345E-02 | 57254 |  | 2.6590E-01 | 92829 |
|  |  |  | 4.9686E-04 | 22757 |  | 9.4338E-02 | 58332 |  | 2.7281E-01 | 93907 |
|  |  |  | 6.3787E-04 | 23835 |  | 9.8376E-02 | 59410 |  | 2.7982E-01 | 94985 |
|  |  |  | 8.1059E-04 | 24913 |  | 1.0247E-01 | 60488 |  | 2.8692E-01 | 96063 |
|  |  |  | 1.0216E-03 | 25991 |  | 1.0663E-01 | 61566 |  | 2.9413E-01 | 97141 |
|  |  |  | 1.2793E-03 | 27069 |  | 1.1087E-01 | 62644 |  | 3.0143E-01 | 98219 |
|  |  |  | 1.5942E-03 | 28147 |  | 1.1518E-01 | 63722 |  | 3.0883E-01 | 99297 |
|  |  |  | 1.9800E-03 | 29225 |  | 1.1958E-01 | 64800 |  | 3.1633E-01 | 100375 |
|  |  |  | 2.4549E-03 | 30303 |  | 1.2406E-01 | 65878 |  | 3.2393E-01 | 101453 |
|  |  |  | 3.0425E-03 | 31381 |  | 1.2862E-01 | 66956 |  | 3.3163E-01 | 102531 |
|  |  |  | 3.7741E-03 | 32459 |  | 1.3328E-01 | 68034 |  | 3.3943E-01 | 103609 |
|  |  |  | 4.6905E-03 | 33537 |  | 1.3802E-01 | 69112 |  | 3.4733E-01 | 104687 |
|  |  |  | 5.8439E-03 | 34615 |  | 1.4285E-01 | 70190 |  | 3.5533E-01 | 105765 |
|  |  |  | 7.2989E-03 | 35693 |  | 1.4778E-01 | 71268 |  | 3.6343E-01 | 106843 |
|  |  |  | 9.1312E-03 | 36771 |  | 1.5279E-01 | 72346 |  | 3.7163E-01 | 107921 |
|  |  |  | 1.1423E-02 | 37849 |  | 1.5790E-01 | 73424 |  | 3.7993E-01 | 108999 |
|  |  |  | 1.4249E-02 | 38927 |  | 1.6310E-01 | 74502 |  | 3.8833E-01 | 110077 |
|  |  |  | 1.7666E-02 | 40005 |  | 1.6839E-01 | 75580 |  | 3.9683E-01 | 111155 |
|  |  |  | 2.1681E-02 | 41083 |  | 1.7377E-01 | 76658 |  | 4.0543E-01 | 112233 |
|  |  |  | 2.6244E-02 | 42161 |  | 1.7925E-01 | 77736 |  | 4.1414E-01 | 113311 |
|  |  |  | 3.1237E-02 | 43239 |  | 1.8482E-01 | 78814 |  | 4.2295E-01 | 114389 |
|  |  |  | 3.6497E-02 | 44317 |  | 1.9049E-01 | 79892 |  | 4.3185E-01 | 115467 |
|  |  |  | 4.1845E-02 | 45395 |  | 1.9624E-01 | 80970 |  | 4.4087E-01 | 116545 |
|  |  |  | 4.7123E-02 | 46474 |  | 2.0210E-01 | 82048 |  | 4.4998E-01 | 117623 |

TABLE 2: This table was developed only for Stainless Steel with a code listed Yield Stress of 25 ksi, and an ultimate strength of 70 ksi. These values are inputs to the equations in Annex 3-D.3. The table starts with zero plastic strain at the proportional limit, and extends to the True Ultimate Stress, which is higher than the Engineering Ultimate Stress.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stainless Steel with Sy/Su = 25/70 ksi** | | | **Table for Input into Property data for Multilinear Isotropic Hardening** | | | | | | | |
| **Plastic Strain** | **Stress** |  | **Plastic Strain** | **Stress** |  | **Plastic Strain** | **Stress** |
| Young's Modulus | 28000 | ksi | **(m/m)** | **(psi)** |  | **(m/m)** | **(psi)** |  | **(m/m)** | **(psi)** |
| Poisson's Ratio | 0.31 |  | 0.00 | 8912 |  | 6.5144E-02 | 44086 |  | 2.2948E-01 | 79260 |
|  |  |  | 1.3141E-05 | 9978 |  | 6.9403E-02 | 45152 |  | 2.3593E-01 | 80326 |
|  |  |  | 3.2194E-05 | 11044 |  | 7.3535E-02 | 46218 |  | 2.4247E-01 | 81392 |
|  |  |  | 5.8871E-05 | 12110 |  | 7.7591E-02 | 47284 |  | 2.4910E-01 | 82458 |
|  |  |  | 9.5174E-05 | 13176 |  | 8.1614E-02 | 48350 |  | 2.5583E-01 | 83523 |
|  |  |  | 1.4344E-04 | 14242 |  | 8.5638E-02 | 49416 |  | 2.6265E-01 | 84589 |
|  |  |  | 2.0636E-04 | 15308 |  | 8.9687E-02 | 50481 |  | 2.6956E-01 | 85655 |
|  |  |  | 2.8709E-04 | 16373 |  | 9.3780E-02 | 51547 |  | 2.7656E-01 | 86721 |
|  |  |  | 3.8934E-04 | 17439 |  | 9.7930E-02 | 52613 |  | 2.8366E-01 | 87787 |
|  |  |  | 5.1749E-04 | 18505 |  | 1.0215E-01 | 53679 |  | 2.9085E-01 | 88853 |
|  |  |  | 6.7686E-04 | 19571 |  | 1.0644E-01 | 54745 |  | 2.9813E-01 | 89919 |
|  |  |  | 8.7405E-04 | 20637 |  | 1.1081E-01 | 55811 |  | 3.0551E-01 | 90985 |
|  |  |  | 1.1174E-03 | 21703 |  | 1.1526E-01 | 56877 |  | 3.1298E-01 | 92050 |
|  |  |  | 1.4178E-03 | 22769 |  | 1.1980E-01 | 57943 |  | 3.2055E-01 | 93116 |
|  |  |  | 1.7898E-03 | 23835 |  | 1.2442E-01 | 59008 |  | 3.2820E-01 | 94182 |
|  |  |  | 2.2529E-03 | 24900 |  | 1.2914E-01 | 60074 |  | 3.3595E-01 | 95248 |
|  |  |  | 2.8341E-03 | 25966 |  | 1.3394E-01 | 61140 |  | 3.4380E-01 | 96314 |
|  |  |  | 3.5705E-03 | 27032 |  | 1.3883E-01 | 62206 |  | 3.5174E-01 | 97380 |
|  |  |  | 4.5125E-03 | 28098 |  | 1.4381E-01 | 63272 |  | 3.5977E-01 | 98446 |
|  |  |  | 5.7273E-03 | 29164 |  | 1.4888E-01 | 64338 |  | 3.6790E-01 | 99512 |
|  |  |  | 7.3008E-03 | 30230 |  | 1.5404E-01 | 65404 |  | 3.7612E-01 | 100577 |
|  |  |  | 9.3355E-03 | 31296 |  | 1.5930E-01 | 66470 |  | 3.8443E-01 | 101643 |
|  |  |  | 1.1940E-02 | 32362 |  | 1.6464E-01 | 67535 |  | 3.9284E-01 | 102709 |
|  |  |  | 1.5210E-02 | 33427 |  | 1.7008E-01 | 68601 |  | 4.0134E-01 | 103775 |
|  |  |  | 1.9191E-02 | 34493 |  | 1.7561E-01 | 69667 |  | 4.0994E-01 | 104841 |
|  |  |  | 2.3849E-02 | 35559 |  | 1.8122E-01 | 70733 |  | 4.1863E-01 | 105907 |
|  |  |  | 2.9052E-02 | 36625 |  | 1.8693E-01 | 71799 |  | 4.2742E-01 | 106973 |
|  |  |  | 3.4590E-02 | 37691 |  | 1.9274E-01 | 72865 |  | 4.3630E-01 | 108039 |
|  |  |  | 4.0224E-02 | 38757 |  | 1.9863E-01 | 73931 |  | 4.4527E-01 | 109104 |
|  |  |  | 4.5747E-02 | 39823 |  | 2.0462E-01 | 74996 |  | 4.5434E-01 | 110170 |
|  |  |  | 5.1026E-02 | 40889 |  | 2.1070E-01 | 76062 |  | 4.6351E-01 | 111236 |
|  |  |  | 5.6007E-02 | 41954 |  | 2.1687E-01 | 77128 |  | 4.7277E-01 | 112302 |
|  |  |  | 6.0698E-02 | 43020 |  | 2.2313E-01 | 78194 |  | 4.8212E-01 | 113368 |

# 6.0 ADDITIONAL REFERENCE MATERIAL AND INFORMATION

A Presentation of the analysis results which includes more detain on the analyses was presented to the Mechanical Safety Subcommittee in the August 2019 meeting.

























































