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RECOMMENDATIONS FOR LINEARIZATION PROCEDURE IN PRESSURE VESSEL-NOZZLE INTERSECTIONS

Carolina Della Ricco Figueiredo and Miguel Mattar Neto

Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN/SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP, Brasil
carolinadellaricco@yahoo.com.br and mmattar@ipen.br

ABSTRACT

The pressure vessel design is a fundamental step during the construction of new pressurized water reactors (PWRs). In these facilities, several safety requirements are necessary to guarantee the protection of workers, community and environment against the release of radioactive materials. The current version of the ASME Code for vessel pressure presents two types of procedures for structural analysis: Design by Standard and Design by Analysis. The Design by Analysis is a more complex procedure and it requires more rigorous analysis and classification of all types of stresses and loading conditions, in order to incorporate smaller safety coefficients. However, precise rules for achieving the various stress categories have not been implemented in the code. For this reason, this work presents a methodology for the stress linearization in nozzle-vessel intersections. The used recommendation is that the line constructed for the linearization should be taken out of transitions elements. So a pressure vessel-nozzle intersection was modeling, analyzed and verified then a discussion of how to perform the Code verifications was presented, as well as a mapping of stress. The lines that were constructed in pressure vessel between transition and structural elements in the longitudinal plane (0º) and lines in structural elements in the nozzle in the transversal plane (90º) presents higher stresses.

1. INTRODUCTION

The pressure vessel design is a fundamental step during the construction of new pressurized water reactors (PWRs). In these facilities, it is necessary several safety requirements that guarantee the protection of workers, community and environment against the release of radioactive materials. It is also required to ensure that the equipment can operate safely under expected and postulated loads.

In the design of nuclear pressure vessels, a widely used standard is the ASME Code [1] which the initial version, published in 1960, introduced an innovation in relation to the previous codes: the introduction of Project by Analysis. The Project by Analysis is an approach where a more detailed stress analysis and advanced techniques are used. As a result, more reliable design is obtained, where the security levels are increased, the safety coefficient is significantly reduced and there is the prevention of the main modes of failure.

The current version of the ASME Code for pressure vessel brings two types of procedures for structural analysis: Design by Standard and Design by Analysis. The Design by Standard is a procedure frequently used in older versions of the code. It is based on shell stress distribution formulas and applied to a limited number of sections located in regular geometries. The used safety coefficients are higher and in the points not covered by the formulas details rules are applied. The Design by Analysis is a more complex procedure. In 1955, committees aimed to reevaluate and propose new criteria for establishing the limit stresses based on new knowledge were created. These committees were asked to develop a new section of the Code. In this approach, a greater number of failure modes than the previous Code version are considered, establishing safety margins. Therefore, it requires more rigorous analysis and classification of all types of stresses and loading conditions, in order to avoid the failure modes predicted for pressure vessels. Also, it is desired to incorporate smaller safety coefficients than the ones used up to then.

However, precise rules for achieving the various stress categories have not been implemented in the code. The presented recommendations are limited to some geometries and load conditions, commonly the axisymmetric conditions. The use of three-dimensional models by applying the finite element analysis makes possible the analysis of more complex models. Nonetheless, the difficulty in evaluating the results and comparing them with the allowed limits has increased. In order to study those problems, a research project was instituted by PVRC called "WRC bulletin 429: 3D Stress Criteria Guidelines for Application" [2], which has the objective of helping with those difficulties, so the problems are modeled with solid finite elements and the stress linearized, separated and classified by ASME Code.

2. METHODOLOGY

The methodology applied in the current study addresses stress classification in pressure vessel-nozzle intersection. It was developed according to references [2], [3] and [4].

2.1. Stress Categorization and Classification

The ASME categorization basically consists in identify the stresses as "Primary stress" (P) and "Secondary stress" (Q). The primary stress is the one caused by mechanical loads and it is limited in order to avoid plastic collapse. The secondary stress is the one that is presents in compatibility and the limits associated with it have the propose to avoid the accumulation of plastic deformation under cyclic load (Ratchetting).

There are three possible ways to classify the stresses: in a point, in a line or in a plane (see Figure 1). Evaluating the stress in a point is a conservative approach because the maximum stress in a section of the considered component is taken and may be it is not necessarily classified as a structural failure.

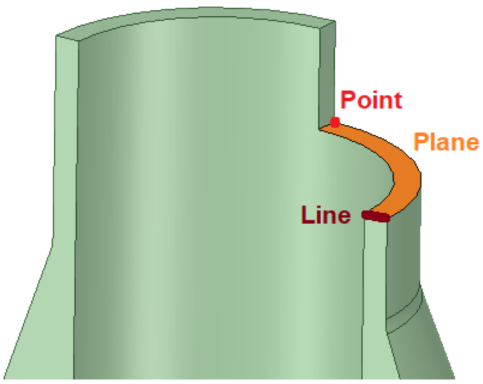

Figure 1: Approaches for stress classification.

The classification in the line and in the plane is appropriate; the line classification is usually utilized. The linearization consists in construct a line over the element thickness and separates the stress in membrane stress, bending stress and peak stress.

The procedure for stress classification on the plane can be implemented through the post-processing of results from the solid element modeling with the aid of spreadsheets.

The PVRC (Pressure Vessel Research Council) funded a research project that created six short term recommendations for using the ASME Code. The first and third are related to the FEM (Finite Element Method). The first short term recommendation suggests the use of FEM only for primary plus secondary stresses. The primary stress must be calculated with FEA (Finite Element Analysis), otherwise using general equilibrium considerations for simple geometries.

The third recommendation brings the appropriated locations to evaluate stresses $P_l + P_b$ and P + Q. It is suggested to evaluated stresses in the basic structural element and not in transition elements. The structural and transitions elements are illustrated in Figure 2. A transition element is an element that connects one structural element to another, with either constant or variable thickness.

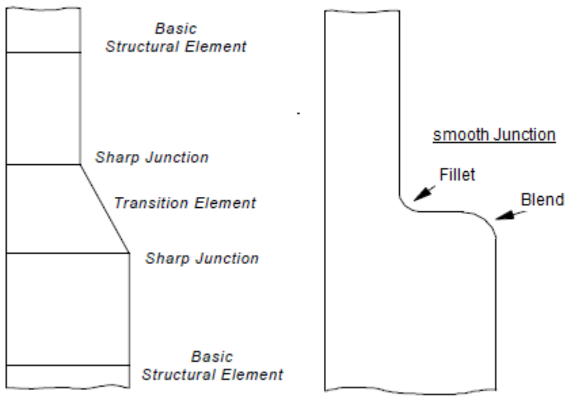

Figure 2: Structural and transition elements [1].

2.2. Stress Classification Lines (SCL)

The stress classification lines (SCL), according to WRC-429, are defined by two points through the vessel thickness and should be parallel to inner, outer and middle surfaces. That not always is possible.

There are some criteria for a SCL been considered valid, which tend to ensure the inaccuracies are minimized. The circumferential and longitudinal stresses distribution in a SCL should be linear. A SCL should be perpendicular to surfaces tangents. Through-thickness stress distribution should be linear or parabolic, depending on surface boundary conditions (zero or non-zero pressure). And through-thickness shear stress should present a parabolic shaped.

Miranda; Faloppa; Neto and Fainer [3] made a stress linearization and classification in a wye junction and it is possible to notice that lines take in transition elements presents irregular and far from the theoretical linear distribution, making the SCL in those locations not appropriated. So, lines created in present work followed those requirements, within an engineering judgment level.

2.3. Linearization Procedure

Linearization approach, according to ASME Code, is the commonly applied in pressure vessel structural analysis. It is used due to the necessity of simulating complex models with 3D solid elements and comparing stress with the ASME code, which was based in shell theory for admissible limits.

The linearization is the approach used in 3D Stress Criteria Guidelines for Application. It consists in construct a line over the element thickness and separates the stress in membrane stress, bending stress and peak stress. Figure 3 shows the typical stress distribution along a line.

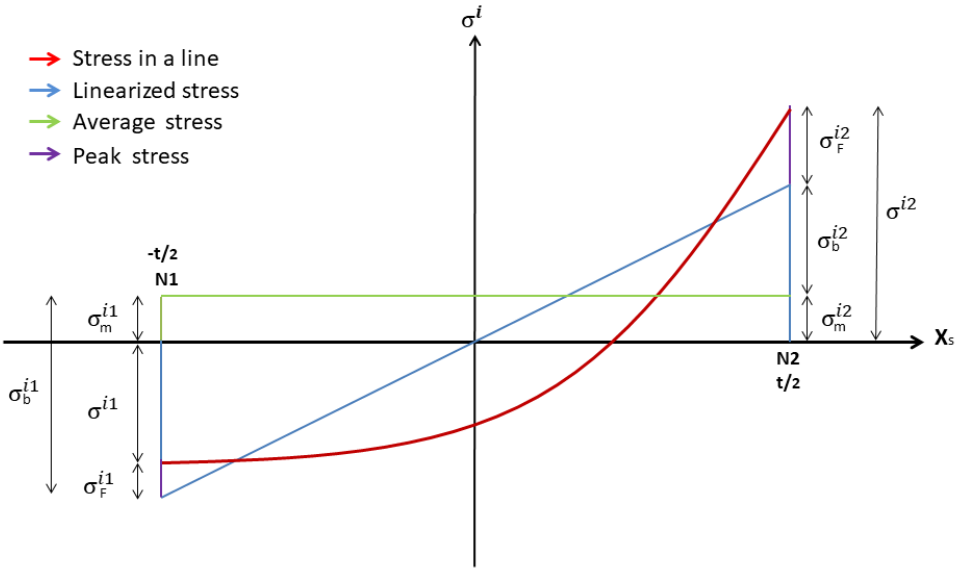

Figure 3: Stress distribution in a line.

Where: σ^i is the stress component i along a line;
t is the thickness of the section;
σ^i_m is the membrane value of a stress component i;
x_s is the coordinate along the line.

For a general 3D case, the stress value of each of the stress components can be calculated by the following equations. Equation (1) is used to calculate the membrane stress, Eq. (2) and Eq. (3) are used to calculate bending stress at the end of the thickness N1 and N2, respectively. The software that is used ANSYS Mechanical [4] and it uses a modification linearization procedure derivate from Kroenke procedure.

$$\sigma_m^i = \frac{l}{t}\int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma^i \partial x_s \qquad (1)$$

$$\sigma_b^{i1} = -\frac{6}{t^2}\int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma^i x_s dx_s \qquad (2)$$

$$\sigma_b^{i2} = -\sigma_b^{i1} \qquad (3)$$

The peak stress value in a point is the difference between the total stress and the sum of membrane and bending stresses.

3. STUDY CASE: PRESSURE VESSEL-NOZZLE MODEL

The study case consists of mapping and classification of the stress in a pressure vessel-nozzle intersection. A simulation was performed with the software ANSYS Mechanical in Nuclear and Energy Research Institute, IPEN-CNEN/SP.

3.1. Geometry

The geometry used in this study is a pressure vessel-nozzle intersection and its dimensions and pressure value is present in WRC-429 as geometry 6, in cylinder-to-cylinder intersection problems. The geometry was modeling using ANSYS Spaceclaim [5]. Although the decay distance of $2{,}5\times\sqrt{R_m \times t}$ suggested in some literature, this study was used $3{,}0\times\sqrt{R_m \times t}$ to guarantee that the loads and the boundary conditions will not influence stress response in the nozzle region.

3.2. Study of Mesh Quality

The geometry was sliced in strategic parts to facilitate the mesh inputs and to obtain results, as it shows in Figure 4.

X. Liping. and G.E.O.Widera [6] makes some mesh size recommendations. In axial directions, the elements must vary in $0{,}02\times\sqrt{R_m \times t}$ in the discontinuity site to $0{,}5\times\sqrt{R_m \times t}$ in decay distance. After that, the elements can be about $1{,}0\times\sqrt{R_m \times t}$. The recommendation for circumference elements is an element every 3.75º to better capture the peak of stress in the region for internal pressure loads. Thus, the recommendation is 96 elements by diameter. For the thickness, tree elements are considered enough.

So, for the first mesh created was set based on those recommendations and the mesh used in the base document so a verification of the numerical model (loads, displacement restriction, symmetry axes) was made. The mesh was refined in order to decrease the numerical uncertainties and carry more reliability to the results without the time processing concern.

To get to the final and refined mesh, tree more meshes were created based on the first one. Table 1 summarized meshes information, as well as nodes and elements numbers. Table 2 brings the differences in linearized stress intensity for the seven SCL in the longitudinal plane (0º) for the four meshes.

Table 1: Meshes information

Mesh	Nodes	Elements	Elements thru the thickness
1	341628	67497	3
2	483173	100528	4
3	657432	141310	5
4	973078	214050	6

Table 2: Differences Between Meshes

SCL_00	Linearized Stress Intensity	Mesh 1 (Mpa)	Mesh 2 (Mpa)	Difference between Mesh 1 and Mesh 2 (%)	Mesh 3 (Mpa)	Difference between Mesh 2 and Mesh 3 (%)	Mesh 4 (Mpa)	Difference between Mesh 3 and Mesh 4 (%)
1	M	185.62	185.63	0.01	185.63	0.00	185.60	0.02
	M+Bo	149.67	149.66	0.01	149.67	0.01	149.65	0.01
	M+Bi	221.57	221.59	0.01	221.60	0.00	221.55	0.02
2	M	187.37	187.38	0.01	187.38	0.00	187.36	0.01
	M+Bo	144.61	144.61	0.00	144.62	0.01	144.60	0.01
	M+Bi	230.14	230.15	0.00	230.14	0.00	230.11	0.01
3	M	194.09	194.10	0.01	194.10	0.00	194.08	0.01
	M+Bo	139.35	139.36	0.01	139.37	0.01	139.36	0.01
	M+Bi	248.83	248.84	0.00	248.83	0.00	248.80	0.01
4	M	208.86	208.93	0.03	208.85	0.04	208.92	0.03
	M+Bo	135.03	134.95	0.06	134.95	0.00	134.91	0.03
	M+Bi	282.76	283.00	0.08	282.83	0.06	283.01	0.06
5	M	96.14	96.21	0.07	96.23	0.02	96.25	0.03
	M+Bo	126.53	126.50	0.02	126.49	0.01	126.54	0.04
	M+Bi	66.06	66.26	0.31	66.32	0.10	66.34	0.02
6	M	116.25	116.24	0.01	116.24	0.00	116.23	0.01
	M+Bo	148.99	148.97	0.01	148.95	0.01	148.93	0.01
	M+Bi	83.51	83.52	0.01	83.53	0.02	83.54	0.01
7	M	112.73	112.66	0.06	112.68	0.02	112.59	0.08
	M+Bo	152.93	152.95	0.01	152.91	0.03	152.92	0.01
	M+Bi	72.53	72.37	0.22	72.45	0.11	72.27	0.24

Although the refinement does not affect significantly the membrane and membrane plus bending stresses, mesh 4 was chosen to facilitate future analyses.

3.3. SCLs construction

In order to classify the stresses in the pressure vessel-nozzle intersections, seven lines were created along with the discontinuities places, four in the pressure-vessel and three in the nozzle, every 10º. As the recommendation suggests creating lines in structural lines, no line was created in transition elements except for the SCLs 4 and 5 which are between structural and transition elements. In the pressure-vessel, SCL 1, 2, 3 and 4 were created separated from each other in a distance of 0,5 x $\sqrt{R_m \times t}$ and SCL 5, 6 and 7 from nozzle were separated in 1,5 x $\sqrt{R_m \times t}$.

Figure 4 illustrates where the SCL were taken, in the perpendicular of the axis X plan (0º). It also illustrates the other plans, where SCL were taken in the same distance from the transition element (discontinuities).

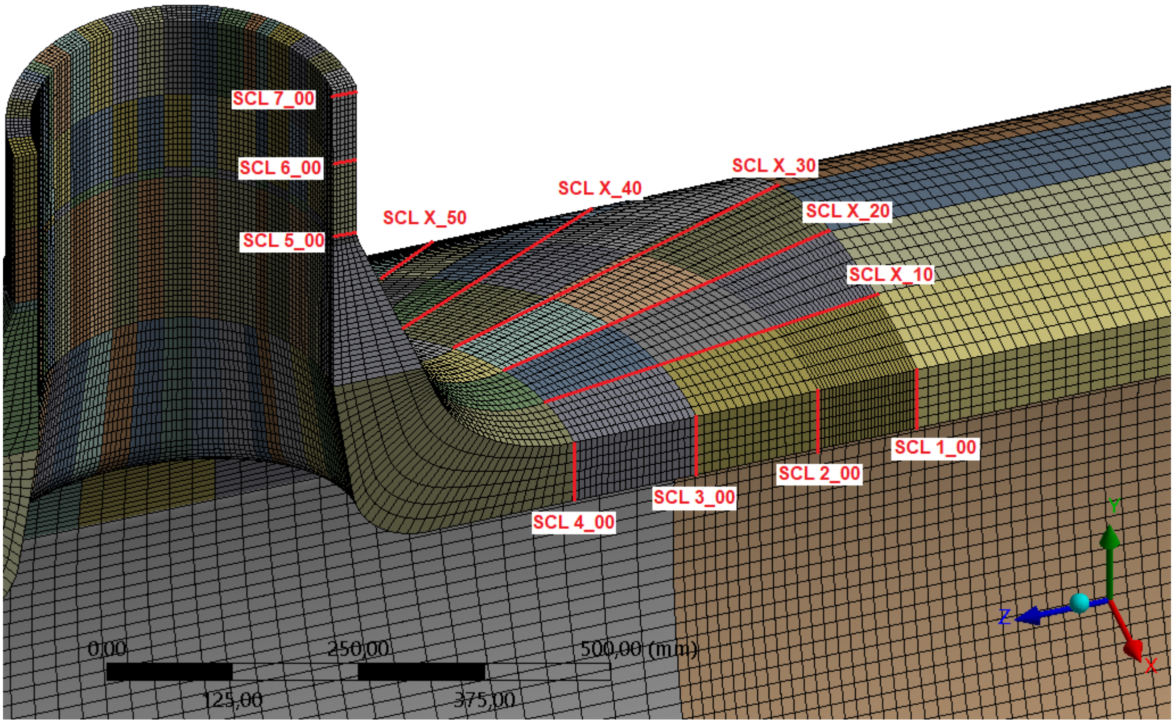

Figure 4: Mesh used in simulation and choice of SCLs

3.4. Results and Discussion

The results from the linearization of SCLs are given in short form by Table 3. It is presented the stress intensity for each of the seven lines in each of ten plan angles (0 to 90º).

From Table 3, it is possible to map the stress behavior along proximities of the discontinuities. SCL 1, 2, 3 and 4, localized in the pressures-vessel, presents the inside membrane plus bending stress bigger than the outside one at 0º. As the plane angle increase, the reverse occurs. They get the same value in an angle of about 45º.

The same occurs in SCL 5, 6 and 7, localized in the nozzle. The outside membrane plus bending stress is bigger than the inside one at 0º and as long as the angle is increased, the reverse occurs. They get the same value in an angle about 40º.

Table 3: Linearized Stress Intensity [Mpa]

SCL_00	Component	Linearized Stress Intensity (Mpa)	SCL_10	Component	Linearized Stress Intensity (Mpa)	SCL_20	Component	Linearized Stress Intensity (Mpa)	SCL_30	Component	Linearized Stress Intensity (Mpa)	SCL_40	Component	Linearized Stress Intensity (Mpa)
	M	185,74		M	186,09		M	186,64		M	186,17		M	185,02
1	M+Bo	147,98	1	M+Bo	151,36	1	M+Bo	159,15	1	M+Bo	169,77	1	M+Bo	179,40
	M+Bi	223,50		M+Bi	221,30		M+Bi	215,26		M+Bi	203,55		M+Bi	191,03
	M	187,45		M	188,13		M	189,54		M	190,39		M	189,95
2	M+Bo	143,15	2	M+Bo	146,90	2	M+Bo	156,31	2	M+Bo	168,90	2	M+Bo	182,40
	M+Bi	231,75		M+Bi	230,10		M+Bi	224,47		M+Bi	213,46		M+Bi	198,09
	M	194,15		M	195,30		M	197,86		M	199,84		M	199,26
3	M+Bo	138,24	3	M+Bo	143,78	3	M+Bo	156,77	3	M+Bo	173,23	3	M+Bo	190,50
	M+Bi	250,06		M+Bi	248,19		M+Bi	241,99		M+Bi	229,65		M+Bi	209,94
	M	209,06		M	211,78		M	216,74		M	220,12		M	218,63
4	M+Bo	134,29	4	M+Bo	144,56	4	M+Bo	165,41	4	M+Bo	188,43	4	M+Bo	211,27
	M+Bi	283,91		M+Bi	283,03		M+Bi	276,16		M+Bi	261,42		M+Bi	235,65
	M	96,23		M	97,40		M	100,39		M	104,35		M	108,53
5	M+Bo	126,61	5	M+Bo	129,92	5	M+Bo	131,85	5	M+Bo	129,53	5	M+Bo	122,89
	M+Bi	66,21		M+Bi	69,35		M+Bi	78,30		M+Bi	91,85		M+Bi	108,25
	M	116,23		M	116,51		M	117,32		M	118,47		M	119,76
6	M+Bo	148,98	6	M+Bo	146,44	6	M+Bo	139,08	6	M+Bo	127,70	6	M+Bo	116,91
	M+Bi	83,48		M+Bi	86,76		M+Bi	96,17		M+Bi	110,51		M+Bi	128,01
	M	112,60		M	112,88		M	113,66		M	114,82		M	116,17
7	M+Bo	152,95	7	M+Bo	149,82	7	M+Bo	140,82	7	M+Bo	127,02	7	M+Bo	110,07
	M+Bi	72,25		M+Bi	76,93		M+Bi	88,26		M+Bi	105,05		M+Bi	124,53
SCL_50	**Component**	**Linearized Stress Intensity (Mpa)**	**SCL_60**	**Component**	**Linearized Stress Intensity (Mpa)**	**SCL_70**	**Component**	**Linearized Stress Intensity (Mpa)**	**SCL_80**	**Component**	**Linearized Stress Intensity (Mpa)**	**SCL_90**	**Component**	**Linearized Stress Intensity (Mpa)**
	M	184,76		M	186,19		M	188,69		M	190,79		M	191,41
1	M+Bo	184,53	1	M+Bo	182,68	1	M+Bo	178,15	1	M+Bo	176,19	1	M+Bo	174,90
	M+Bi	185,82		M+Bi	191,34		M+Bi	200,38		M+Bi	205,87		M+Bi	207,92
	M	188,51		M	188,02		M	189,07		M	190,68		M	191,25
2	M+Bo	192,54	2	M+Bo	196,68	2	M+Bo	194,39	2	M+Bo	189,88	2	M+Bo	187,82
	M+Bi	184,79		M+Bi	181,19		M+Bi	186,42		M+Bi	192,66		M+Bi	194,73
	M	196,56		M	192,49		M	188,31		M	185,69		M	184,75
3	M+Bo	205,70	3	M+Bo	215,75	3	M+Bo	218,43	3	M+Bo	213,03	3	M+Bo	209,71
	M+Bi	187,83		M+Bi	169,40		M+Bi	159,55		M+Bi	159,72		M+Bi	159,87
	M	211,00		M	196,35		M	177,69		M	156,84		M	146,32
4	M+Bo	230,63	4	M+Bo	159,63	4	M+Bo	117,94	4	M+Bo	251,21	4	M+Bo	250,15
	M+Bi	201,24		M+Bi	244,01		M+Bi	251,38		M+Bi	76,81		M+Bi	53,46
	M	112,47		M	115,80		M	118,33		M	119,91		M	120,44
5	M+Bo	112,90	5	M+Bo	100,77	5	M+Bo	88,66	5	M+Bo	79,04	5	M+Bo	165,79
	M+Bi	125,47		M+Bi	141,53		M+Bi	154,50		M+Bi	162,90		M+Bi	75,17
	M	121,02		M	122,09		M	122,89		M	123,38		M	123,55
6	M+Bo	97,96	6	M+Bo	82,74	6	M+Bo	69,52	6	M+Bo	60,14	6	M+Bo	56,63
	M+Bi	146,56		M+Bi	163,93		M+Bi	178,07		M+Bi	187,27		M+Bi	190,46
	M	117,51		M	119,26		M	119,60		M	120,17		M	120,36
7	M+Bo	91,98	7	M+Bo	73,83	7	M+Bo	60,83	7	M+Bo	51,48	7	M+Bo	48,03
	M+Bi	145,45		M+Bi	167,14		M+Bi	180,94		M+Bi	191,31		M+Bi	194,91

Figure 5 shows the stress behavior along the angle variation for the SCL presents in pressure-vessel that presents the highest membrane and membrane plus bending stress: SCL 4.

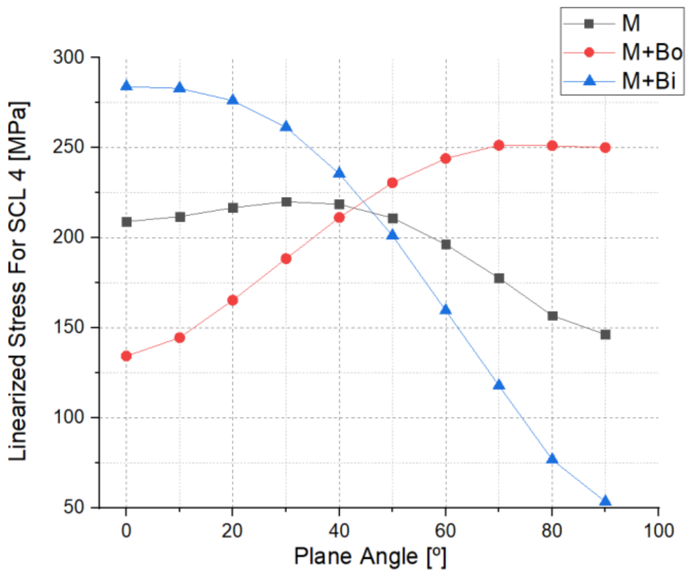

Figure 5: Stress Behavior for SCL 4 [MPa]

Figure 6 shows the stress behavior along the angle variation for the SCL presents in the nozzle that presents the highest membrane and membrane plus bending stress: SCL 6 and 7, respectively.

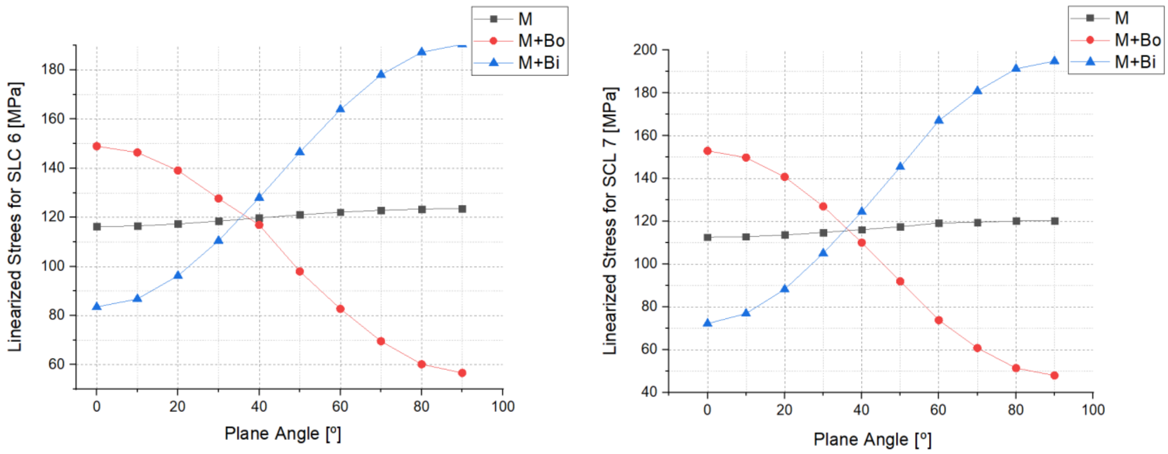

Figure 6: Stress Behavior for SCL 6 and 7 [MPa]

Observing Table 3 and the stress behavior presented in the graphics from Figure 5 and Figure 6, is possible to conclude that, for this case, the highest membrane plus bending stress is always applied in angle 0 or 90º.

Table 4 brings the highest values of membrane and membrane plus bending stress that each component is exposed. The material considered was the usual steel used in the pressure vessel construction, SA508 Class 3. Its yield stress, from ASME proprieties [7], for temperature about 300ºC, is 259,5 MPa. This way, the maximum allowable stress S_m = 173 MPa.

Table 4: Stress Classification

	SCL	Component	Classification	Max. Stress (Mpa)	ASME Limit (Mpa)	Verification
Pressure-vessel	4_30	M	P_l	220,12	259,5	ok
	4_00	M+Bi	P + Q	283,91	519	ok
Nozzle	6_90	M	P_m	123,55	173	ok
	7_90	M+Bi	$P_m + P_b$	194,91	259,5	ok

The stress classification is done based on SCL location. In pressure-vessel, the highest membrane and membrane plus stresses are localized in SCL 4. As SCL 4 is close to the discontinuities, between structural and transition elements, the stresses may present a portion due the compatibly. It is classified as primary location stress P_l and primary plus secondary stress P + Q, respectively.

In the nozzle, the highest membrane stress is in SCL 6 and is classified as primary membrane stress P_m. The highest membrane plus bending stresses are localized in SCL 7 and it is classified as primary membrane plus primary bending $P_m + P_b$. As both are far from discontinuities, the stresses are caused only due to mechanical loads and are classified as primary. ASME limits the P_m, P_l, $P_m + P_b$ and P + Q stresses as S_m, 1,5 x S_m, 1,5 x S_m and 3,0 x S_m, respectively.

It is possible to notice that the highest stress in the nozzle is in the transversal plane (90º) and membrane plus bending occurs in the longitudinal plane. The vessel highest membrane stress occurs in a 30º plane, although the difference between membrane stress of SCL 4_00 and SCL 4_30 is about 5%.

4. CONCLUSIONS

The study presents the verification of pressure vessel-nozzle intersection stresses done according to the ASME Code as well as a mapping of stress. Only stresses due to the internal pressure were considered, once the aim is to emphasize the procedure of the stress classification and linearization. These procedures are common in the nuclear area and it is still an open issue. The SCLs have their stress classified based on their location: lines taken out of discontinuities have their membrane stress classified as P_m and membrane plus bending stress classified as $P_m + P_b$. Lines near the discontinuities have their stress classified as P_l for membrane stress and P + Q for membrane plus bending stress. Finally can be highlighted that lines constructed on pressure vessel between transition and structural elements on the longitudinal plane (0º) and lines constructed on the nozzle in structural elements on the transversal plane (90º) present higher stresses.

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