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SEISMIC PERFORMANCE OF INDUSTRIAL PRESSURE VESSELS: PARAMETRIC INVESTIGATIONS OF SIMPLIFIED MODELING APPROACHES FOR VULNERABILITY ASSESSMENT

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Abstract. *The present paper presents the up-to-date results of an on-going research effort aiming to develop novel, efficient and reliable computational (analytical) methods for assessing the vulnerability of pressure vessel structures as well as at advancing their performance-based seismic design framework. More specifically, various potential simplifications of a refined model of a pressure vessel in order to develop a surrogate one are investigated in detail and the derived results and conclusions lead to the proposal of guidelines for the development of surrogate, cost-effective yet reliable, models for pressure vessels.*

1 INTRODUCTION

Until now the various procedures in the literature used to assess the vulnerability of pressure vessels are focused to a specific structural type and as a result refined (detailed) finite element models were used [1]. In a previous research effort by the authors [2], a methodology was proposed for the derivation of fragility curves for various types of industrial pressure vessels. In order for this methodology to be applicable to a large number of pressure vessels the computational effort for analyses has to be minimized; for this reason, the proposed methodology was based on static nonlinear analysis and four damage states were defined directly on the derived pushover curves. A further significant reduction of the time for analyses can be achieved by using surrogate models instead of refined ones, the development of which is the subject of the present paper. Such models were also used in other studies [3, 4] to assess the seismic performance of pressure vessels, but without any investigation of the effect of their inherent simplification assumptions on their accuracy in describing the seismic response of pressure vessels. For this reason, in the present work several simplification approaches that can be applied to a refined model so as to produce a surrogate one are extensively studied and the derived conclusions are then used to form specific guidelines for the development of surrogate models for pressure vessels that can be reliably used in assessment procedures.

2 INVESTIGATION OF SIMPLIFICATION APPROACHES FOR THE DEVELOPMENT OF SURROGATE MODELS

The structural system of a pressure vessel consists of the the spherical shell, the supporting columns and, in some cases the column-bracing trusses. In a refined model the first two parts are modeled with shell elements; the latter one is modeled either with frame elements or, in case wherein braces cannot resist compression forces due to their negligible buckling strength, with hook elements placed at the end of each brace which are activated only in tension.

The development of a surrogate model is usually based on the following modeling approaches:

- Simplified modeling of braces,
- Simplified modeling of the spherical shell,
- Simplified modeling of columns

In the following, these modeling simplifications are parametrically investigated in order to determine the range and limits of their applicability and their effect on the accuracy of the derived surrogate models.

In a previous paper by the authors [2] two actual pressure vessels were used for investigation purposes, one without braces (PV1) and one with braces (PV2). For these two vessels two refined finite element models were developed in ABAQUS (AB1 and AB2, respectively) using the S4R and S3R shell elements for the discretization of the spherical shell and columns and the T3D2 truss element for braces. Based on these two models, 12 additional finite element models (Fig. 1) were derived for parametric investigations, through addition or removal of braces and through differentiation of the column thicknesses so as to correspond to EC3 classification thresholds for section classes 1, 2 and 3. The same models and terminology are used in the present research effort. The interested reader can refer to [2] for further details.

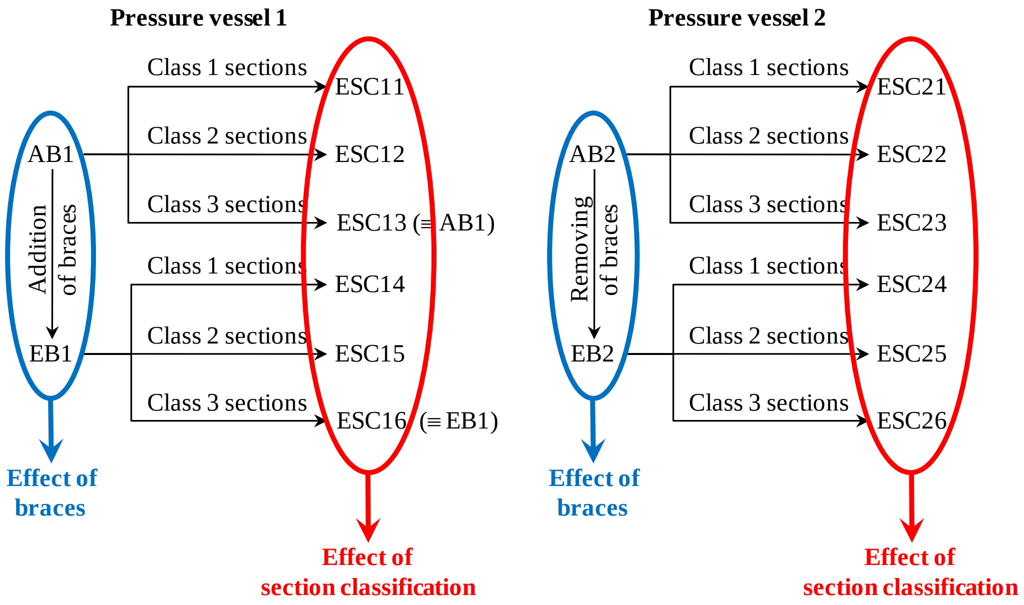
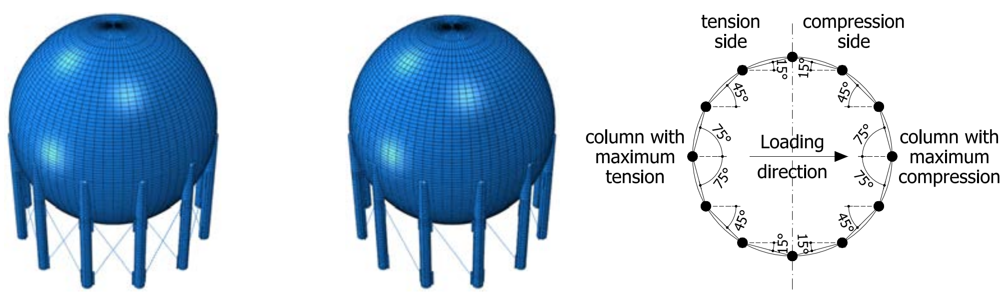


Figure 1: Pressure vessel models used for parametric investigations.

2.1 Simplified modeling of braces

According to the refined method for modeling braces (Fig. 2a), i.e. placing of hook (i.e. tension-only activated) elements at one of their ends, the horizontal elastic stiffness of the vessel is successively increased, due to the successive activation of braces in tension, resulting in a corresponding decrease to the eigenperiod of the translational mode. For this reason, it is very difficult to use this method in response spectrum analysis and also, in performance-based design, to define an appropriate inelastic equivalent single degree of freedom (ESDOF) system to estimate the target displacement on the basis of pushover analysis procedures.

A simplified approach to tackle these problems is to remove any hook elements, keeping only braces in tension in the model (Fig. 2b). In this way, the horizontal elastic stiffness of the vessel, and consequently the period of its translational mode, are constant making this method more appropriate to use in response spectrum analysis and in the definition of the inelastic ESDOF system. However, modeling only the tension braces results in an antisymmetric structural system, which, for the symmetric operating loads, i.e. the internal pressure and the self weight, leads to a small horizontal displacement that actually does not exist.



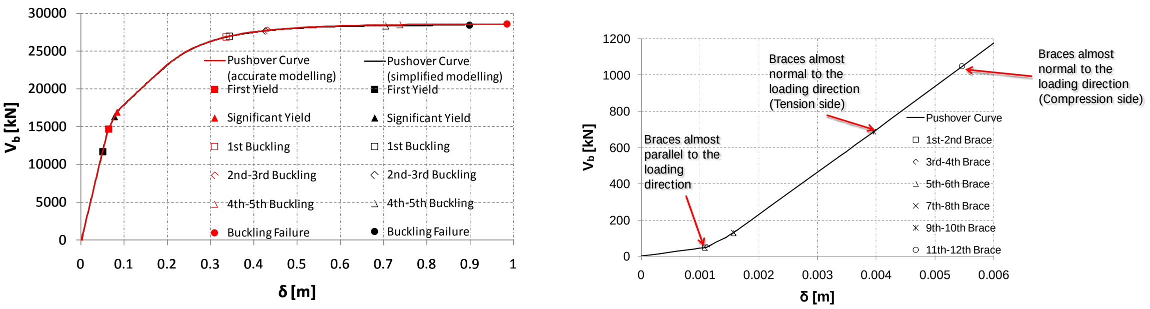
a. Refined modelling (all braces and hook elements at one of their ends)

b. Simplified modelling (only braces in tension)

c. Modelling details (pushover)

Figure 2: Modeling of braces.

Both aforementioned modeling methods are applied to the pressure vessel AB2 and the derived pushover curves are shown in Fig. 3, while the results at their characteristic points are given in Table 1. When all braces are modeled, the derived pushover curve (Fig. 3a – red line) has an increasing slope at its initial stage (Fig. 3b) due to the successive activation of braces in tension. At first, due to the self weight and the internal pressure all braces are inactive, since they cannot carry the resulting compression force. Then, when the horizontal force is applied the stiffness of the vessel has its minimum value, corresponding to an unbraced vessel, until a displacement of 0.011m wherein the first two braces (the nearest parallel ones to the loading direction on the tension side of the vessel – see Fig. 2c) are activated.. The other two braces at the compression side of the vessel are activated at the next step. Then, the slope remains constant until the activation of the next four braces at two successive steps for a horizontal displacement of 0.016m, firstly the two at the tension side and then the two at the compression side. These braces are the ones with an angle of 45° with respect to the loading direction. The last four braces that are activated are the almost normal ones to the loading direction. Again, the two braces at the tension side of the vessel are activated first and next the two at the compression side for displacements 0.040m and 0.055m, respectively. After all tension braces are activated the horizontal stiffness of the vessel remains constant, reaching its maximum value until the first yield.



a. Pushover curves

b. Successive activation of braces at the beginning of the pushover curve

Figure 3: Simplified modeling of braces – Pushover curves.

Quantity	Refined modeling	Simplified modeling	Difference [%]
Yield displacement [m] (Yield of braces)	0.064	0.050	-28.0
Ultimate displacement [m]	0.985	0.898	-14.8
Yield force [kN] (Yield of braces)	14703	11693	-25.7
Ultimate force [kN]	28595	28454	-0.5

Table 1: Simplified modeling of braces – Values at characteristic points of pushover curves.

Tension braces with smaller angle to the loading direction (almost parallel) are activated first and the ones with larger angle (almost normal) are activated last. In other words, the activation sequence is proportional to the contribution of tension braces to the horizontal stiffness of the structure. It should be noted that all tension braces are activated for a horizontal displacement of 0.055m which is very small compared to the ultimate displacement of 0.985m. For this reason, the derived pushover curve (Fig. 3a – red line) can be practically considered as linear in the elastic range with a slope that corresponds to the stiffness of the vessel with all tension braces activated.

From the comparison between the refined and the simplified modeling methods (Fig. 3a and Table 1) it observed that in the simplified model (i.e. when only tension braces are taken into account) the first yield takes place earlier at an average percentage of 28%, while the ultimate displacement at a smaller and acceptable percentage of 14.8%. The significant yield, i.e. the point that corresponds to 10% reduction of the secant stiffness, and all column buckling (with a small exception at the first column buckling), also take place slightly (i.e. 3% to 5%) earlier. The horizontal displacement for the symmetric operating loads due to the antisymmetry of the structural system of the simplified model is only 0.0011m, i.e. very small compared to the yield displacement of 0.050m and of course the ultimate displacement of 0.898m. Hence, it is concluded that in pushover investigations, modeling only the braces in tension is an acceptable simplification.

2.2 Simplified modeling of the spherical shell

A next step and probably the most critical issue in the development of a surrogate model is the modeling of the spherical shell in a simplified manner. An approach that is commonly used [3, 4] is the substitution of the spherical shell with a rigid body connection of the column heads. In the following, the applicability range of this simplification is investigated.

2.2.1 Effect of internal pressure

Due to the in plane rigidity of the assumed rigid body connection, moments and shear forces at columns mainly due to the internal pressure and secondary due to the self weight are not taken into account. In order to investigate the effect of the internal pressure, models AB1 and AB2 are analyzed with and without the corresponding internal pressure. The derived pushover curves are shown in Fig. 4. It is observed that in model AB1 the overall shape of the two pushover curves is the same and only specific characteristic points differ at percentages varying from 17.5% for the first yield to 4.3% for the ultimate displacement. In model AB2 the ultimate displacement is significantly larger (64.3%) when the internal pressure is ignored, while the difference for the ultimate force (strength) is only 3.3%.

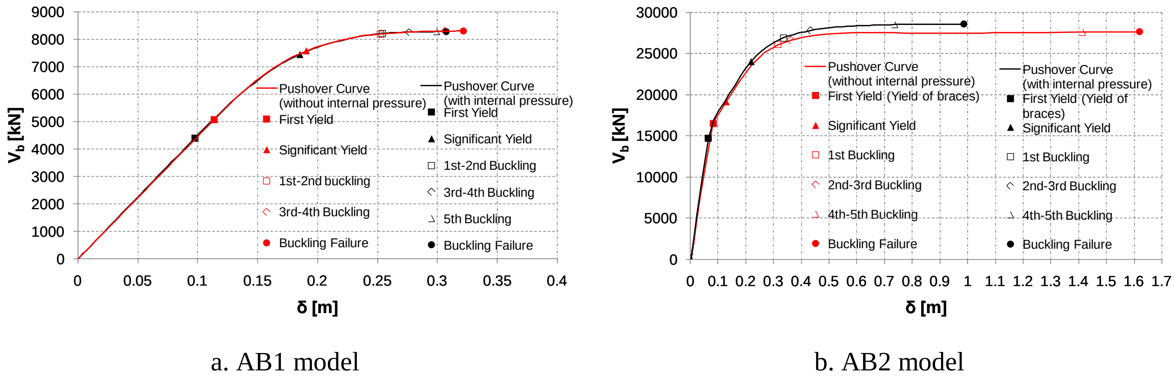
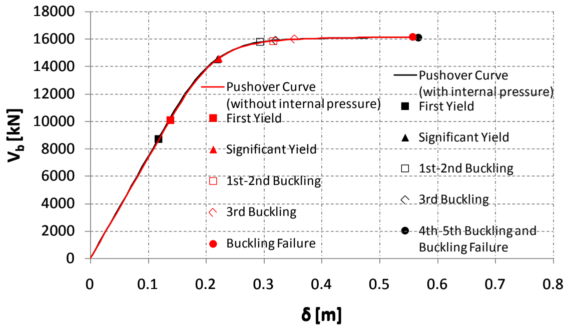
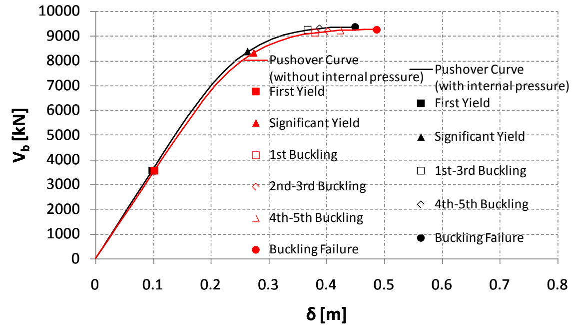


Figure 4: Effect of internal pressure – Pushover curves of AB1 and AB2 models.

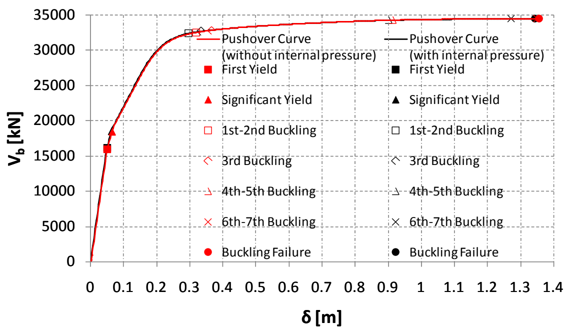
The next step is to investigate whether the presence of braces and/or the class the column sections cause the observed overestimation of the ultimate displacement in model AB2. For this reason all models used for parametric analyses in [2] are analyzed for both cases, i.e. with and without internal pressure. Some of the derived pushover curves are shown in Fig. 5 and the comparison of the corresponding ultimate displacements is given in Table 2.



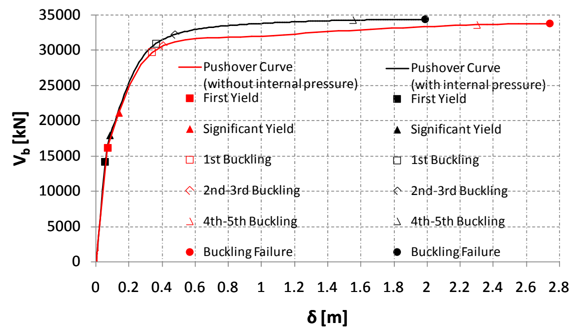
a. ESC11 model



b. ESC26 model



c. ESC14 model



d. ESC21 model

Figure 5: Effect of internal pressure – Pushover curves of models in [2].

MODEL	t [mm]	D [mm]	BRACES	$d_{ultimate}$ [m] With internal pressure	$d_{ultimate}$ [m] Without internal pressure	Difference [%]
ESC11	33	1016	NO	0.566	0.556	-1.8
ESC12	23	1016	NO	0.378	0.370	-2.1
ESC13≡AB1	18	1016	NO	0.315	0.318	0.9
ESC14	33	1016	YES	1.344	1.356	0.9
ESC15	23	1016	YES	0.747	0.740	-0.9
ESC16≡EB1	18	1016	YES	0.522	0.532	1.8
AB2	25-30	1100	YES	0.985	1.618	64.2
ESC21	40	1100	YES	1.989	2.743	37.9
ESC22	28	1100	YES	0.990	0.660	-33.3
ESC23	22	1100	YES	0.794	0.599	-24.6
EB2	25-30	1100	NO	0.534	0.549	2.8
ESC24	40	1100	NO	0.765	0.628	-18.0
ESC25	28	1100	NO	0.536	0.558	4.1
ESC26	22	1100	NO	0.449	0.487	8.6

Table 2: Effect of internal pressure –Comparison of ultimate displacements of models in [2].

From Fig. 5 and Table 2 it is observed that in all models derived from the original pressure vessel PV1, the pushover curves for the two cases, i.e. with and without internal pressure, practically coincide and the corresponding ultimate displacements differ only at negligible percentages varying from 0.9% to 2.1%. Only specific characteristic points are significantly different, e.g. the first yield in model ESC11. On the contrary, in all models derived from the original pressure vessel PV2 the derived pushover curves differ in both strength (with small variations up to 4%) and ultimate displacement (with significant variations ranging from a 33.3% underestimation up to a 64.2% overestimation). Consequently, the similarities in all models of PV1 and the differences in all models of PV2 are not due to the presence of braces or the column section class.

The other major difference between the two pressure vessels is the thickness of the spherical shell, which in PV1 is 74.5mm and in PV2 is 42mm, i.e. significantly smaller. Hence, in order to investigate whether the reduced shell thickness is responsible for the observed differences in PV2 models, a set on 14 new models without braces are created on the basis of EB2 model. More specifically, in all new models the shell thickness is 42mm and the internal pressure 1120 kN/m^2 (i.e. same as those of vessel PV2). In seven models the thickness of column sections is 25mm and in the other 7 is 30mm. At three of the seven models the diameter of columns corresponds to the limit of each of three section classes (Class 1, 2 and 3), while in the remaining four models columns' diameter corresponds to 1/3 and 2/3 of the difference in diameter between two subsequent classes. The derived pushover curves of some models are shown in Fig. 6 and the comparison of the corresponding ultimate displacements are given in Table 3.

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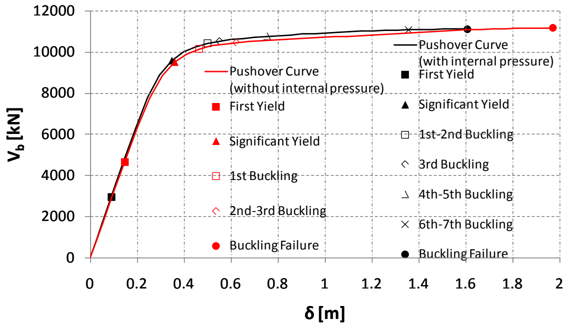
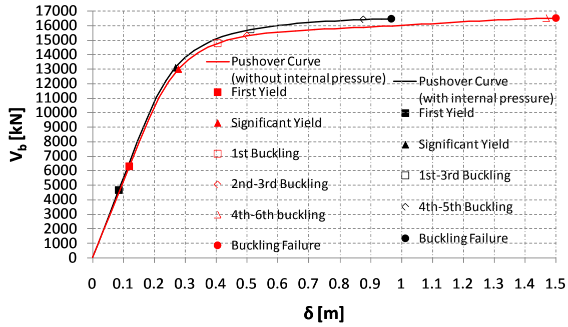
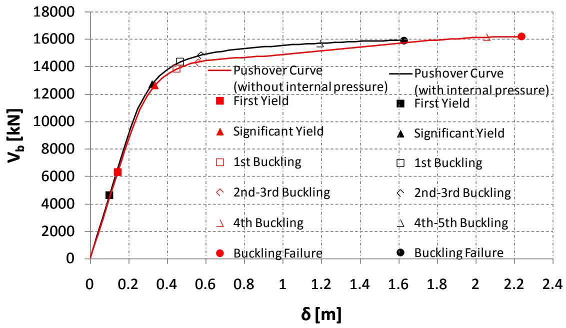


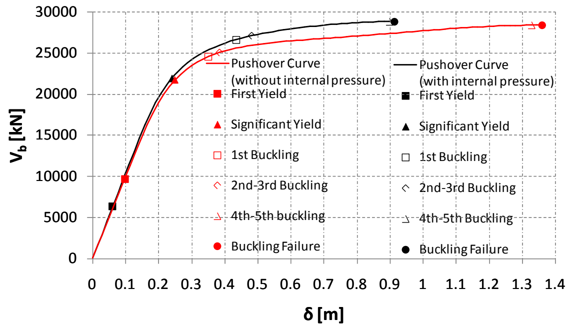
a. T25D0984 model



b. T25D1183 model



c. T30D1057 model

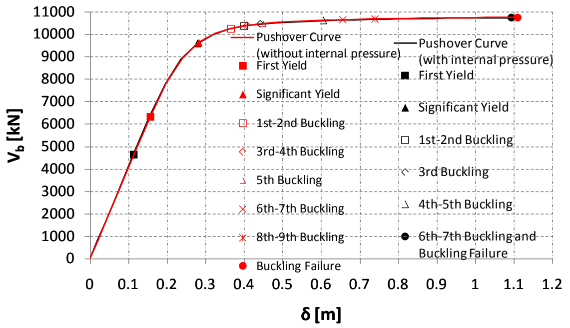


d. T30D1433 model

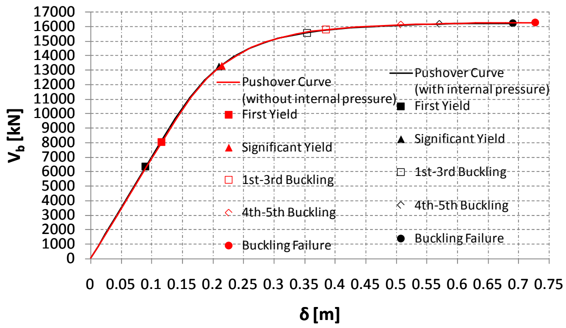
Figure 6: Effect of internal pressure – Pushover curves of new models based on EB2 – Shell thickness 42 mm.

MODEL	t_{shell} [mm]	t_{column} [mm]	D [mm]	Section Class	$d_{ultimate}$ [m] With internal pressure	$d_{ultimate}$ [m] Without internal pressure	Difference [%]
T25D0750	42	25	750	1	1.072	1.405	31.1
T25D0867	42	25	867		1.562	1.834	17.4
T25D0984	42	25	984		1.606	1.971	22.7
T25D1100	42	25	1100	2	0.536	0.558	4.1
T25D1183	42	25	1183		0.966	1.499	55.2
T25D1267	42	25	1267		0.898	1.289	43.6
T25D1350	42	25	1350	3	0.711	0.972	36.7
T30D0930	42	30	930	1	2.158	2.493	15.5
T30D1057	42	30	1057		1.627	2.235	37.4
T30D1184	42	30	1184		1.335	1.930	44.6
T30D1310	42	30	1310	2	1.179	1.679	42.4
T30D1433	42	30	1433		0.913	1.360	48.9
T30D1557	42	30	1557		0.889	1.378	55.1
T30D1680	42	30	1680	3	0.716	1.037	44.9

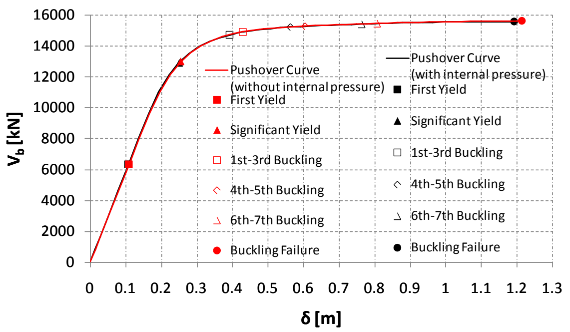
Table 3: Effect of internal pressure – Comparison of ultimate displacements of new models based on EB2 – Shell thickness 42mm.



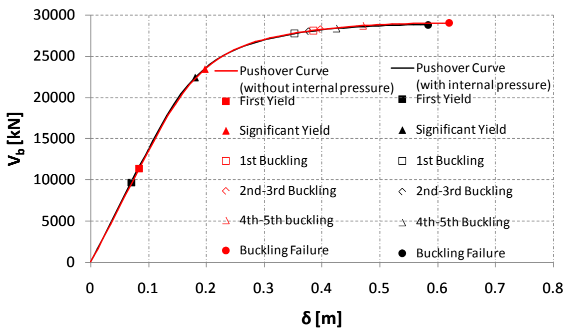
a. T25D0984 model



b. T25D1183 model



c. T30D1057 model



d. T30D1433 model

Figure 7: Effect of internal pressure – Pushover curves of new models based on EB2 – Shell thickness 74.5 mm.

MODEL	t_{shell} [mm]	t_{column} [mm]	D [mm]	Section Class	$d_{ultimate}$ [m] With internal pressure	Without internal pressure	Difference [%]
T25D0750	74.5	25	750	1	0.670	0.678	1.3
T25D0867	74.5	25	867		0.812	0.823	1.4
T25D0984	74.5	25	984		1.093	1.110	1.6
T25D1100	74.5	25	1100	2	0.431	0.439	1.7
T25D1183	74.5	25	1183		0.691	0.727	5.3
T25D1267	74.5	25	1267		0.624	0.635	1.8
T25D1350	74.5	25	1350	3	0.555	0.565	1.7
T30D0930	74.5	30	930	1	1.232	1.252	1.6
T30D1057	74.5	30	1057		1.191	1.213	1.8
T30D1184	74.5	30	1184		0.912	0.950	4.2
T30D1310	74.5	30	1310	2	0.748	0.779	4.1
T30D1433	74.5	30	1433		0.583	0.620	6.3
T30D1557	74.5	30	1557		0.624	0.623	-0.3
T30D1680	74.5	30	1680	3	0.581	0.593	2.2

Table 4: Effect of internal pressure – Comparison of ultimate displacements of new models based on EB2 – Shell thickness 74.5 mm.

It is observed that in all models the derived pushover curves for the two cases (with and without internal pressure) show small differences (up to 5%) in strength, and significant differences (up to 55.2%) in the ultimate displacement. Furthermore, in all cases the ultimate displacement is constantly overestimated when the internal pressure is not taken into account.

Then, the thickness of the spherical shell is increased to 74.5 mm and the internal pressure to 2400 kN/m^2, i.e. same as those of vessel PV1, and the 14 models are analyzed again. Some of the derived pushover curves are shown in Fig. 7 and the comparison of the corresponding ultimate displacements are given in Table 4. In this case, in all models the derived pushover curves practically coincide and the ultimate displacements differ only at an acceptable maximum percentage of 6.3% (similar to the case of all models derived from PV1)

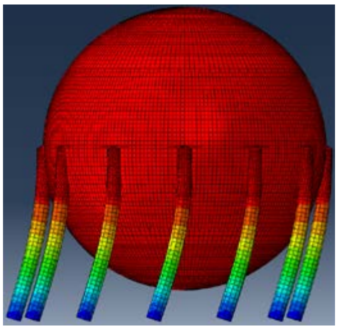
The above analysis shows that when the shell thickness is relatively small, the ultimate displacement is mainly overestimated when the internal pressure is not considered. Of course, this is not on the safety side, since the vessel seems to have significantly larger ductility than it really has. When the thickness of the spherical shell is increased, the overestimation in the ultimate displacement, and consequently in the ultimate ductility, decreases. Hence, the substitution of the spherical shell with a rigid body connection between the heads of columns that does not take into account the stresses from internal pressure is a valid simplification only when the shell thickness is sufficiently large so as to be practically undeformable.

2.2.2 Effect of the consideration of column heads as rotationally fixed

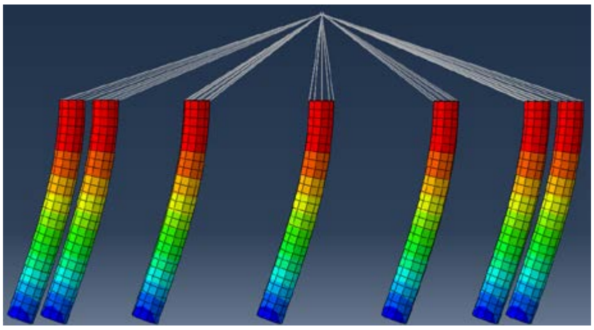
In a refined model columns allow for a small rotation at their heads, which cannot be modeled during the substitution of the shell with a rigid body connection (due to its out of plane rigidity) and, as a result, column heads are considered as rotationally fixed.

In order to investigate the effect of this simplification a surrogate model is created with the shell substituted by a rigid body connection and the columns modeled with shell elements and having their real height, i.e. from their base up to the beginning of their connection to the shell.

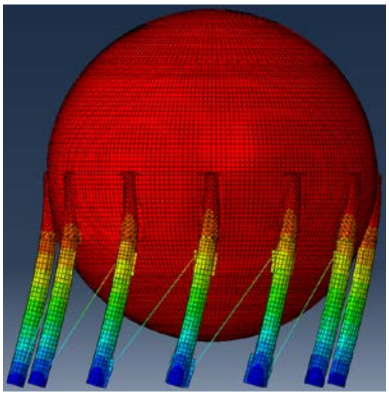
Then, modal and pushover analysis are performed; the derived mode shapes for the translational mode are shown in Fig. 8 and the corresponding periods are given in Table 5, while the pushover curves are shown in Fig. 9 (a and c) and the corresponding differences at characteristic points are given in Table 6.



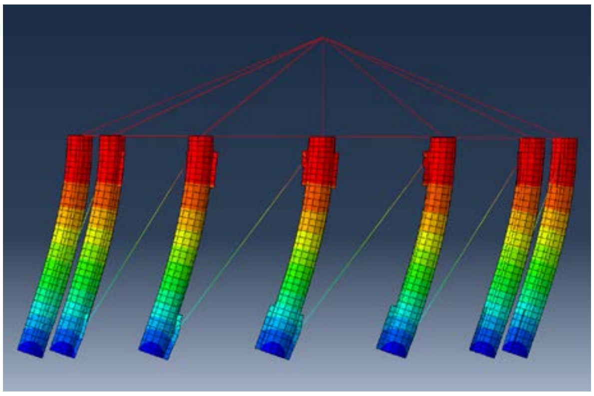
a. AB1 refined model



b. AB1 surrogate model with shells



c. AB2 refined model



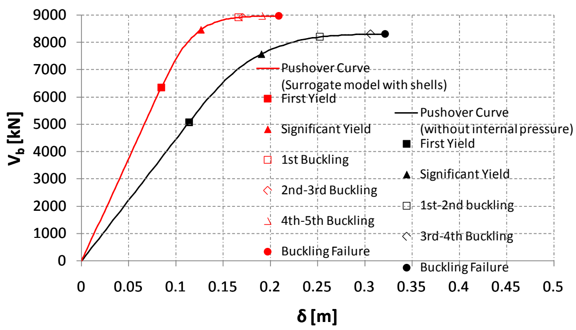
d. AB2 surrogate model with shells

Figure 8: Effect of the consideration of column heads as rotationally fixed – Translational mode shapes of : (a) AB1 and (c) AB2 refined models and (b,d) surrogates with shell-modeled columns.

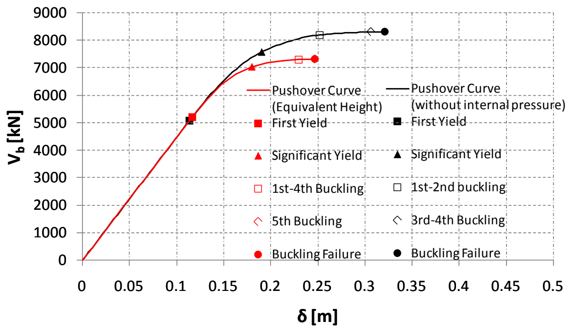
MODEL	Period [sec]		Difference [%]
	Refined model	Surrogate model with shells	
AB1	1.53	1.22	20.3
AB2	0.72	0.61	15.3

Table 5: Effect of the consideration of column heads as rotationally fixed – Translational modal periods of AB1 and AB2 refined and surrogate with shells models.

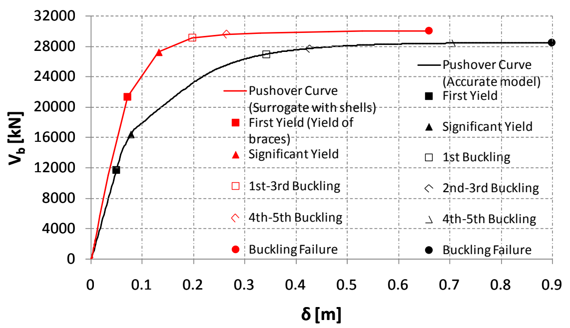
From Table 5 it is observed that the eigenperiod of the translational mode in PV1 is significantly increased by 20.3% when the column heads are considered as rotationally fixed, since columns in the surrogate model are stiffer than those in the refined one, resulting to a 68.6% increase of the horizontal elastic stiffness (see Table 6). In case of PV2, the contribution of columns in the horizontal stiffness of the pressure vessel is smaller, due to the presence of braces, and the corresponding increases are somewhat smaller (15.3% for the eigenperiod and 43.8% for the horizontal elastic stiffness - see Table 7).



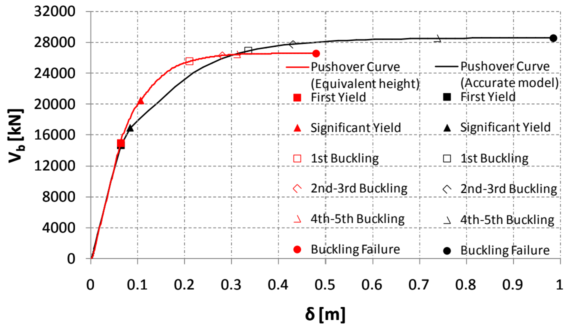
a. AB1 model



b. AB1 model with equivalent height



c. AB2 model



d. AB2 model with equivalent height

Figure 9: Effect of the consideration of column heads as rotationally fixed – Pushover curves of AB1 and AB2 refined and surrogate with shells models.

From Fig. 9 (a and c) and Table 6 it is firstly observed that in both cases surrogate models are stiffer than the refined ones when column heads are considered as rotationally fixed, not only in the elastic range, as previously mentioned, but in the whole range of the response. More specifically, the ultimate displacements are smaller by 34.9% for AB1 and 33.0% for AB2, while the strength is larger, varying from a 25.0% increase at the yield point to 8.0% at the ultimate point for AB1 and from a 45.3% increase at the yield point to 5.0% at the ultimate point for AB2.

Height of columns	Quantity	Refined model	Surrogate model with shells	Difference [%]
Real	Yield displacement [m]	0.114	0.084	-26.3
	Ultimate displacement [m]	0.321	0.209	-34.9
	Yield force [kN]	5079	6348	25.0
	Ultimate force [kN]	8310	8971	8.0
	Elastic stiffness [kN/m]	44660	75300	68.6
Equivalent	Yield displacement [m]	0.114	0.117	2.6
	Ultimate displacement [m]	0.321	0.247	-23.1
	Yield force [kN]	5079	5213	2.6
	Ultimate force [kN]	8310	7321	-11.9
	Elastic stiffness [kN/m]	44660	44660	0.0

Table 6: Effect of the consideration of column heads as rotationally fixed – Values at characteristic points of pushover curves for models of AB1.

Height of columns	Quantity	Refined model	Surrogate model with shells	Difference [%]
Real	Yield displacement [m]	0.064	0.072	12.5
	Ultimate displacement [m]	0.985	0.660	-33.0
	Yield force [kN]	14703	21367	45.3
	Ultimate force [kN]	28595	30036	5.0
	Elastic stiffness [kN/m]	240000	345000	43.8
Equivalent	Yield displacement [m]	0.064	0.063	-1.6
	Ultimate displacement [m]	0.985	0.480	-51.3
	Yield force [kN]	14703	15016	2.1
	Ultimate force [kN]	28595	26603	-6.7
	Elastic stiffness [kN/m]	240000	240000	0.0

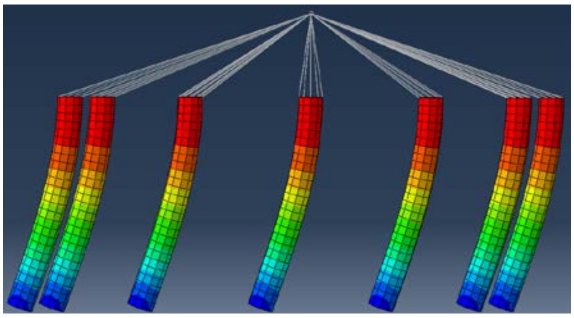
Table 7: Effect of the consideration of column heads as rotationally fixed – Values at characteristic points of pushover curves for models of AB2.

In order to make the surrogate models less stiff in order to comply with the refined ones, a common practice is to increase the height of the columns [3, 4] keeping their heads rotationally fixed. In the present study the column height is increased until the elastic stiffness of the surrogate model becomes equal to the elastic stiffness of the refined one. Following an iterative procedure it was found that for AB1 the column height has to be increased by 50% of the height of the shell-to-column connection, while in AB2 by 33% of the same height. In the two new surrogate models pushover analyses were performed and the derived pushover curves are shown in Fig. 9 (b and d), while the differences at characteristic points are given in Tables 6 and 7. It is observed that for both models the response in the elastic range is almost similar, as expected, and the differences at the yield point are negligible (about 2%). Going to the inelastic branch of the response curve it is observed that now both strength and ultimate displacements are smaller in the surrogate models the former at a acceptable percentage (11.9% for AB1 and 6.7% for AB2) and the latter with a significantly larger percentage (23.1% for AB1 and 51.3% for AB2). In addition, in the surrogate model of AB2 the stiffness after the yielding of braces is not reduced as sharply as in the corresponding refined model (after the significant yield, Figs. 9c and 8d), because the increase of the column height results to larger length of braces, thus smaller stiffness, and to larger angle with respect to the horizontal direction, hence a smaller contribution to the horizontal stiffness of the pressure vessel. In conclusion, since the use of an equivalent column height describes the elastic response sufficiently and the inelastic response on the safety side (regarding the vulnerability of the pressure vessel), it is a acceptable method to implement in order to counteract the increase in stiffness caused by the consideration of column heads as rotationally fixed.

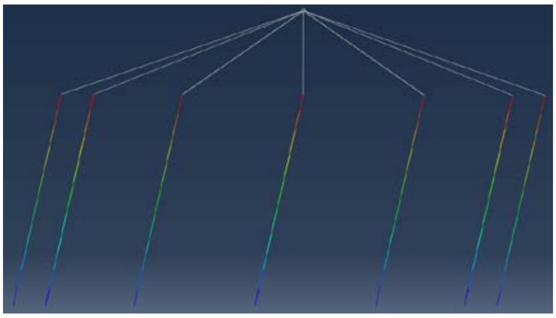
2.3 Simplified modeling of columns

Having substituted the spherical shell with a rigid body connection between column heads, the next step is to model the columns in a simpler manner with frame elements. The major aspect that has to be dealt with is the proper modeling of the inelastic behavior. More specifically, in the refined model a distributed plasticity model is used, wherein each shell element is provided with the inelastic stress-strain relationship of steel. In case of the surrogate model the use of frame elements implies the use of a lumped plasticity model, wherein point hinges are placed at the ends of frame elements.

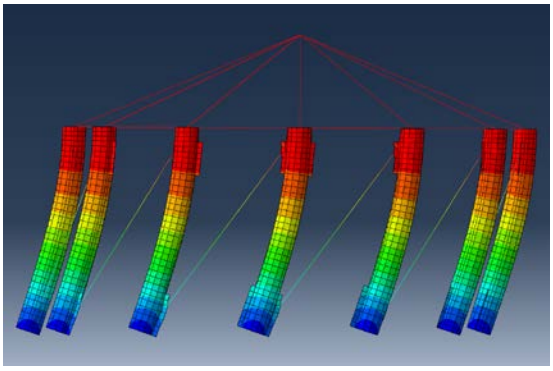
In each point hinge the inelastic behavior is implemented through use of a specific moment-chord rotation (M-θ) diagram. In general, such a diagram can be adopted by various proposals found in the literature [4] but it is not ensured that it will (and most probably will not) match the inelastic behavior of the distributed plasticity model of the refined model (or the surrogate model with shell-modeled columns). Hence, in order to eliminate the differences between the two plasticity models, and consequently modeling of columns with shell and frame elements to become directly comparable, pushover analysis of each shell-modeled column with its corresponding axial force was performed and the derived pushover curve was converted to a M-θ diagram which was then used for the plastic hinge at the end of columns. In our study, since the columns of the vessels under investigation are pinned at their bases, a plastic hinge was introduced only at the top of each column. In the new surrogate model with frame elements, modal and pushover analyses were performed; the derived mode shapes are shown in Fig. 10 and the modal periods are given in Table 8. The derived pushover curves are shown in Fig. 11 and the comparison of strength and displacements at characteristic points are given in Table 9.



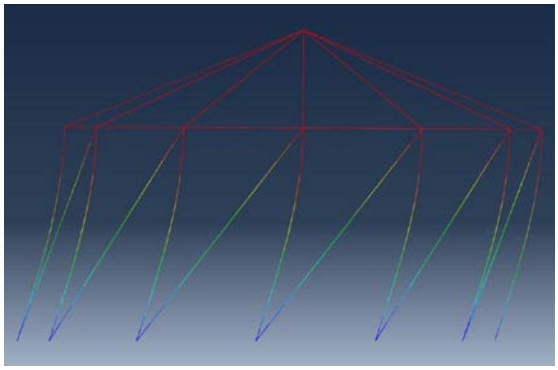
a. AB1 surrogate model with shells



b. AB1 surrogate model with frames



c. AB2 surrogate model with shells



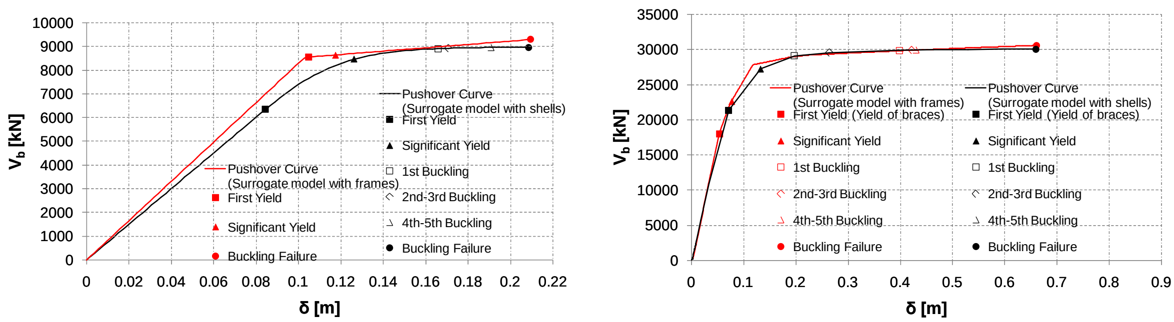
d. AB2 surrogate model with frames

Figure 10: Simplified modeling of columns – Translational mode shapes of AB1 and AB2 surrogate models with shells and frames.

MODEL	Period [sec] Surrogate model with shells	Surrogate model with frames	Difference [%]
AB1	1.220	1.250	2.5
AB2	0.606	0.614	1.3

Table 8: Simplified modeling of columns – Modal periods of AB1 and AB2 surrogate models with shells and frames.

In regard to the modal analysis results it is observed that in both AB1 and AB2 models the difference in modal periods is negligible (2.5% and 1.3%, respectively). In regard to the pushover analysis results it is observed that for model AB1 there is an acceptable difference of 10.2% in the elastic stiffness, which in case of AB2 model becomes negligible (only 1.2%) due to the presence of braces. Also negligible are the differences in the ultimate strength with (3.6% and 1.8% for each model), while there is no difference for ultimate displacements in either model. Conversely, the observed difference at the yield point is significant (varying from 15.7% to 34.9%), since the interaction between moment and axial force (M-N interaction) is not taken into account at the lumped plasticity model. However, overall the observed differences are acceptable, and it can be concluded that modeling of columns with frame elements produces similar results with shell modeling provided that appropriate measures are taken so that the corresponding distributed and lumped plasticity models are compatible.



a. AB1 model b. AB2 model

Figure 11: Simplified modeling of columns – Pushover curves of AB1 and AB2 surrogate models with shells and frames.

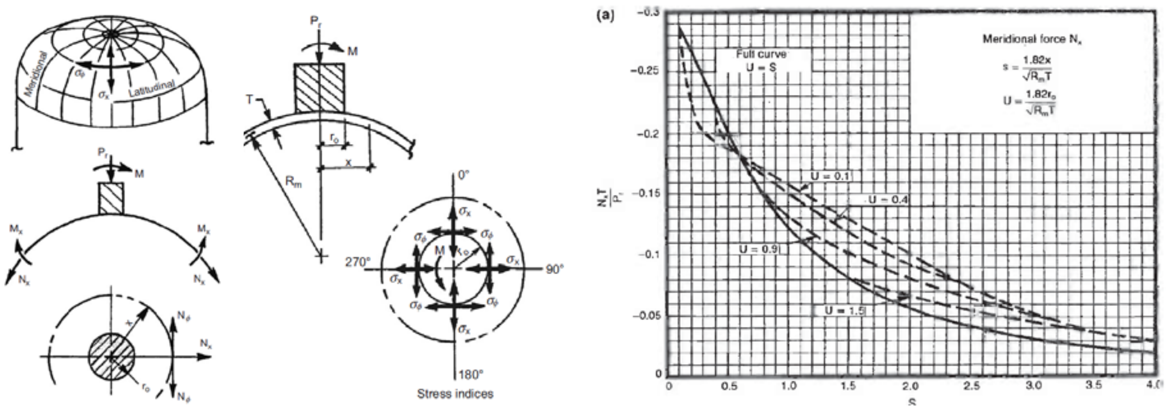
Pressure vessel	Quantity	Surrogate model with shells	Surrogate model with frames	Difference [%]
PV1	Yield displacement [m]	0.084	0.105	25.0
	Ultimate displacement [m]	0.209	0.209	0.0
	Yield force [kN]	6348	8562	34.9
	Ultimate force [kN]	8971	9298	3.6
	Elastic stiffness [kN/m]	75300	83000	10.2
PV2	Yield displacement [m]	0.072	0.054	-25.0
	Ultimate displacement [m]	0.660	0.660	0.0
	Yield force [kN]	21367	18017	15.7
	Ultimate force [kN]	30036	30575	1.8
	Elastic stiffness [kN/m]	344100	348300	1.2

Table 9: Simplified modeling of columns – Values at characteristic points of pushover curves for AB1 and AB2 surrogate models with shells and frames.

2.4 Analytical calculation of stresses at shell-to-columns connections

When a surrogate model with shell or frame-modeled columns is used, the connection between the pressure vessel and the columns is not modeled as in the case of a refined model. However, the developing stresses at the interconnection points in general have to be calculated, so as to check whether the material has reached its yield or in the worst case, its failure point.

For this reason a theoretical procedure proposed in [6] was used in order to estimate the elastic stresses developed at the shell-to-column connection (Fig. 12). It is noted that to the authors' knowledge, no analytical procedure is proposed in the literature for the calculation of stresses developed in the inelastic range of the response. According to this procedure (named as *Procedure 7-5* in [6], pp. 465-472), the elastic stresses in a spherical shell due to external loads (moment M and radial force P_r) imposed by a circular attachment with radius r_0 at a distance $x \geq r_0$ (Fig. 12a) are calculated using nomograms (Fig. 12b) derived from [7] and [8].



a. Stress and sign conventions

b. Nomograms

Figure 12: Calculation of elastic stresses at the shell-to-column connection (from D.R. Moss, M. Basic, *Pressure vessel design manual*, *4th Edition*).

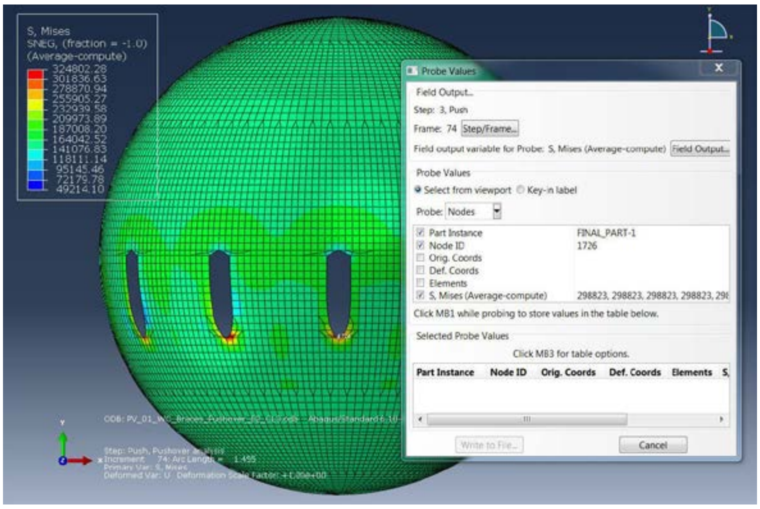


Figure 13: Von Mises stress at the shell-to-column connection of the column with the maximum compression – AB1 model.

The aforementioned procedure is applied to pressure vessel PV1 and specifically to the column with the maximum compression, since it is the critical one regarding the stresses at the shell-to-column connection at the ultimate point of the pushover curve. The derived results are then compared with those from the corresponding numerical model AB1 in Table 10, while in Fig. 13 the derived Von Mises stress at the shell at the bottom of its connection to the column with maximum compression is shown. The observed results between the theoretical procedure and those of the numerical model are negligible (0.25%), thus confirming the validity of the FE model, at least within the elastic behavior range.

Stress	Numerical Model	Theoretical	Difference [%]
Latitudinal [kPa] (Circumferential)	279267	278581	-0.25%
Meridional [kPa]	315139	315684	0.17%
Von Mises [kPa]	298823	298865	0.01%

Table 10: Analytical calculation of stresses in shell-to-column connections – Comparison of results between refined model and analytical procedure.

Given the absence of a theoretical procedure, the FE models were used to numerically predict the inelastic stresses at shell-to-column connections. More specifically, for all cases the developed stresses were checked and it was found that at the ultimate displacement point the stresses at all shell-to-column connections were below the failure point of steel. This means that in general a properly designed pressure vessel will not fail due to stress failure of the spherical shell, since the failure due to buckling of columns typically precedes it.

3 CONCLUSIONS

In the present study various approaches for the development of surrogate models for pressure vessels in order to be used in assessment procedures, such as vulnerability (fragility) assessment methodologies, were extensively investigated resulting to the following conclusions and guidelines :

- For pushover analysis purposes, modeling of braces in tension only by common frame elements is an acceptable simplification over the refined modeling, wherein all braces are taken into account, together with hook (tension-only activated) elements at one of their ends.
- The spherical shell can be substituted by a rigid body connection with the column heads in cases where its thickness is large enough for the shell to be practically undeformable.
- The height of columns should be increased in order to alleviate the increase in their stiffness due to the restriction of the rotation at their top imposed by the substitution of the spherical shell with the rigid body connection. In case of pressure vessels without braces this increase is around 50% of the height of the shell-to-column connection, while in case of pressure vessels with braces this increase is around 33% of the interconnection height.
- Modeling of columns with frame elements will produce similar results as with their modeling with shell elements only in case where the lumped plasticity model used in frames is derived using the results from a pushover analysis of the column modeled with shells.
- In properly designed vessels, the stresses developed at the shell-to-column connections are in general not expected to be the critical failure factor, since the failure due to buckling of columns typically precedes it. However, if the need arises a theoretical procedure described in [6] can be applied with an acceptable accuracy at the results, but only in the elastic range of the response. Regarding inelastic stresses there is not any procedure in the literature for their analytical calculation and resort to numerical analysis using refined FE models is necessary.

4 ACKNOWLEDGEMENTS

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