Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2010
June 6-11, 2010, Shanghai, China

OMAE2010-20423

CRUSHING AND WET COLLAPSE OF FLOWLINE CARCASSES: A THEORETICAL-EXPERIMENTAL APPROACH

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ABSTRACT

The present paper brings together theoretical predictions and experimental results, comparing crushing tests results as well as carcass wet collapse tests. The theoretical models are of two kinds: (i) numerical (FE) and (ii) analytical. The first kind is a restricted 3D version of a finite element model. The second kind is based on classic assumptions of equivalent ring behavior. Discussion is made on the real yield stress value to be adopted, as well as on the pertinence of geometric hypotheses. Sensitivity analyses, regarding ovalization and helical pitch are also presented.

Keywords: Flowline, internal carcass, crushing tests, collapse, numerical model, analytical model.

INTRODUCTION

The interlocked carcass is the innermost layer of a flexible pipe and is designed to withstand high external pressures in case of failure of the external sheath. This failure is usually known as wet collapse.

On the other hand, simple crushing tests may be a quite useful source of theoretical and practical information. Besides, such tests may provide specific data on plastic deformation of the carcass and on its implications in establishing limit loads for laying operation, pigging inspection as well as for predicting carcass wet collapsing.

Analytical, numerical modeling and experimental techniques are joined to construct a theoretical-experimental methodology able to deal with the wet collapse failure mechanism.

A summary of experimental results is presented, followed by some theoretical considerations on analytical and numerical modeling. Crushing experiments simulations are addressed and used to provide additional information to the wet collapse models. Comparisons with experimental results show very good agreement.

The present paper is the companion to another one, [1], presented in the same conference and focused solely on measurement techniques and experimental results on crushing.

Both are result of a development project on flexible pipes, encompassing global and local structural analysis, flow assurance, gas permeation issues, material selection and fabrication processes, as well as installation and reliability.

SUMMARY OF EXPERIMENTAL RESULTS

Table 1, presents the main geometric characteristics of the tested samples, for the two flexible pipe carcasses under investigation. Figure 1 shows examples of 2.5 and 4in pipes samples.

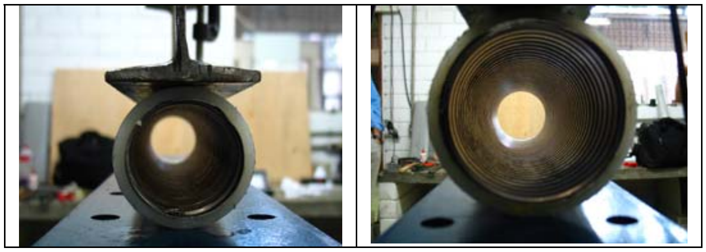

Figure 1. 2.5 and 4inches flexible pipe samples.

Table 1: Main characteristics of the 2½" and 4" samples

Samples of 2½ inches	
Length [mm]	393
Nominal ID [mm]	63.5
OD* [mm]	82.6
L/D (length over ID)	6.19
L/p (length over carcass pitch)	44.2
Thickness of Pressure Sheath [mm]	5
Samples of 4 inches	
Length [mm]	508
Nominal ID [mm]	101.6
OD* [mm]	120.0
L/D (length over ID)	5
L/p (length over carcass pitch)	44.2
Thickness of Pressure Sheath [mm]	5

Collapse Tests

Collapse tests were carried out at Prysmian hyperbaric chamber laboratory. Details on experimental procedures may be found in ref. [2]. All samples were pre-pressurized for 24 hours. After that, the pressure was increased up to the collapse of the structure. Table 2 presents the collapse pressure for both pipes. The experimental average value, as well as the upper and lower statistical limits are also presented. The statistic upper limit is taken as the average value plus 3 times the standard deviation; the statistic lower limit is taken as the average value less 3 times the standard deviation. Assuming a Gaussian distribution, such limit values bound a 99.7% confidence interval.

Crushing Tests

The crushing tests were carried out by LIFE&MO team at Laboratory of Structures and Structural Materials of the Department of Structures and Geotechnical Engineering at the Polytechnic School of the University of São Paulo. Details on experimental procedures and techniques can be found in the references [3], [4]and in the companion paper, ref. [1].

Table 2: Experimental results: 2.5in and 4in samples.

2.5in sample nr.	Collapse Pressure [MPa]	Fraction Filled
3	12.08	0.79
4	12.41	0.79
5	12.82	0.79
6	13.09	0.79
7	13.18	0.79
8	12.45	0.76
9	15.07	0.75
10	15.50	0.75
Average	13.33	0.78
Standard Deviation	1.27	0.019
Upper Stats Limit	17.14	0.83
Lower Stats Limit	9.52	0.72

4in Sample nr.	Collapse Pressure [MPa]	Fraction Filled
14	7.07	0.82
15	7.40	0.79
16	7.49	0.82
19	7.67	0.82
20	7.13	0.82
21	7.41	0.82
Average	7.36	0.82
Standard Deviation	0.23	0.012
Upper Stats Limit	8.04	0.85
Lower Stats Limit	6.69	0.78

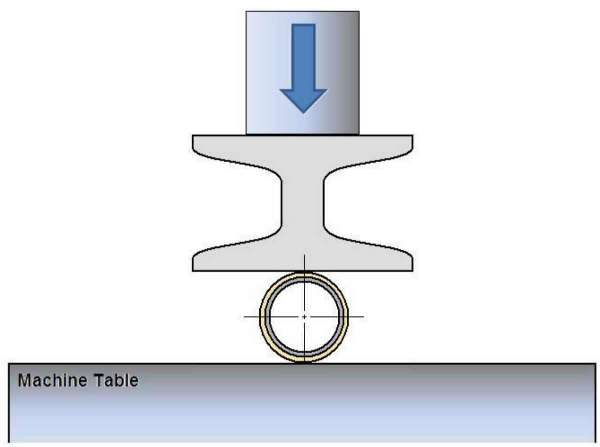

Figure 2: Schematic arrangement for compression load application; [1].

Figures 3 and 4 present, as function of the applied load, horizontal and vertical diameter variations measured with 3 samples of 2.5in and 4in flexible pipe carcasses; see [1]. The loading plane is vertical, so that the horizontal direction is perpendicular to the load.

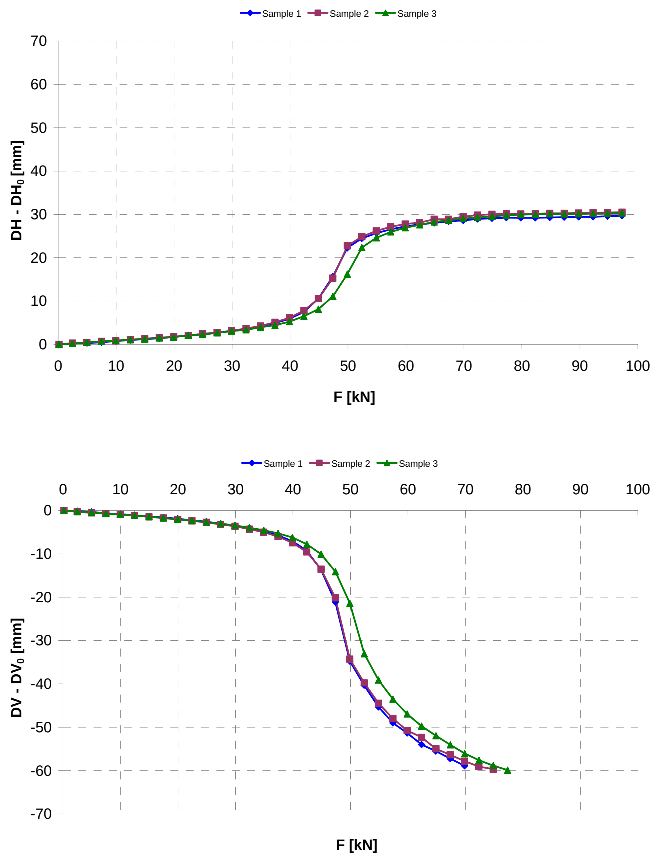

Figure 3: Horizontal and vertical diameter variations: 2.5in pipe samples.

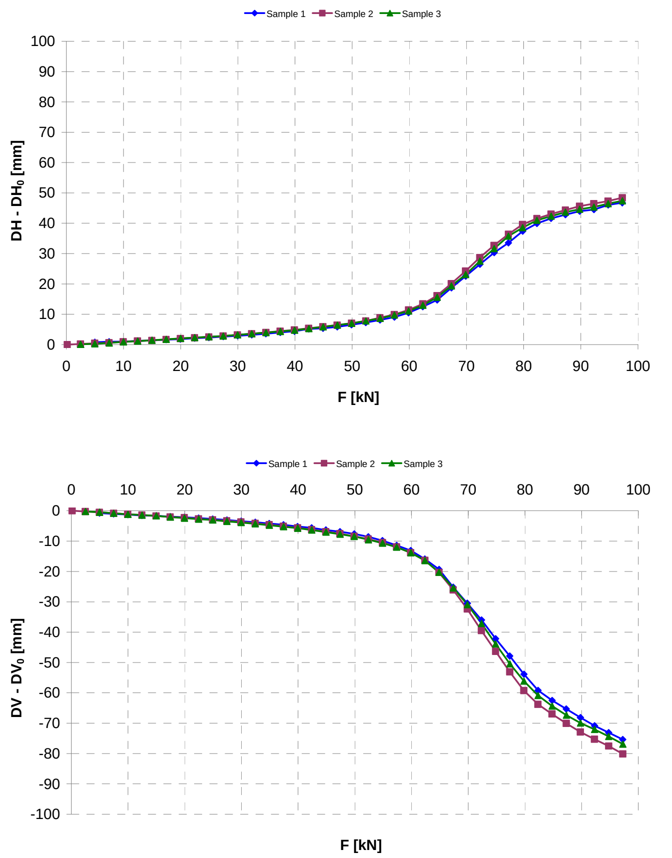

Figure 4: Horizontal and vertical diameter variations: 4in pipe samples.

THEORETICAL CONSIDERATIONS

A simple analytical equivalent ring model

An equivalent ring model is adopted to represent the carcass structural behavior, as described in [5]. Let q_0 be the radial pressure loading per unit arch length. Let also J be the moment of inertia and a be the radius of the equivalent ring. A nondimensional load parameter may be defined as

$$\lambda = \frac{q_0 a^3}{EJ} \tag{1}$$

Let α be the rotation of the ring section and θ the polar coordinate. It can be easily shown that the following eigenvalue problem governs the linear elastic stability of the equivalent ring,

$$\frac{d^2\alpha}{d\theta^2} + \kappa^2\alpha = 0 \qquad \kappa^2 = 1 + \lambda \tag{2}$$

Applying a common periodicity condition and disregarding the non deformable solution, the characteristic roots $\kappa = 2,3,...$ are easily found, such that the well known critical load values may be obtained as

$$q_{0cr} = \frac{\lambda EJ}{a^3} = (\kappa^2 - 1)\frac{\lambda EJ}{a^3} \quad . \tag{3}$$

The first free ring critical loading parameter value is, therefore, $\lambda_{cr} = 3$, corresponding to $\kappa = 2$.

Wet Collapse

Let us consider the carcass as a ring of equivalent thickness t, cross section A and initial ovalization of amplitude $\delta = w_0/a << 1$. If linearity and a (relatively) small load parameter λ are considered, it can be easily shown, [6], that the maximum (compressive) stress along the ring is given by

$$\sigma_{\max} = \frac{\lambda EJ}{a^2}\left(\frac{1}{A} + \frac{1}{1-\lambda/\lambda_{cr}}\frac{w_0}{a}\frac{at}{2J}\right) \quad . \tag{4}$$

A simple yielding criterion, $\sigma_{\max} = \sigma_y$, leads then to the following second-order algebraic equation for the nondimensional yielding load, λ_y,

$$\left(\frac{\lambda_y}{\lambda_{cr}}\right)^2 - \left(1 + \frac{1}{\lambda_{cr}}\frac{Aa^2}{J}\frac{\sigma_y}{E} + \frac{atA}{2J}\frac{w_0}{a}\right)\left(\frac{\lambda_y}{\lambda_{cr}}\right) + \left(\frac{1}{\lambda_{cr}}\frac{Aa^2}{J}\frac{\sigma_y}{E}\right) = 0 \tag{5}$$

or, in terms of yielding pressure, p_y,

$$\left(\frac{p_y}{p_{cr}}\right)^2 - \left(1 + \frac{A}{ab}\frac{\sigma_y}{p_{cr}} + \frac{atA}{2J}\frac{w_0}{a}\right)\left(\frac{p_y}{p_{cr}}\right) + \left(\frac{A}{ab}\frac{\sigma_y}{p_{cr}}\right) = 0 \tag{6}$$

where b is the width of the equivalent ring.

However, the interlocked carcass is not, in fact, a ring. The simpler model that can be thought of, for correcting the equivalent ring assumption, is a single geometric correction parameter model of heuristic nature. For, let the critical nondimensional load parameter and the critical instability pressure be redefined as

$$\begin{aligned} \lambda_{cr}^* &= K\lambda_{cr} \\ p_{cr}^* &= Kp_{cr} \quad . \\ 0 &< K \le 1 \end{aligned} \tag{7}$$

The yielding criterion would then be written,

$$\left(\frac{\lambda_y}{\lambda_{cr}^*}\right)^2 - \left(1 + \frac{1}{\lambda_{cr}^*}\frac{Aa^2}{J}\frac{\sigma_y}{E} + \frac{atA}{2J}\frac{w_0}{a}\right)\left(\frac{\lambda_y}{\lambda_{cr}^*}\right) + \left(\frac{1}{\lambda_{cr}^*}\frac{Aa^2}{J}\frac{\sigma_y}{E}\right) = 0 \tag{8}$$

or, in terms of yielding pressure,

$$\left(\frac{p_y}{p_{cr}^*}\right)^2 - \left(1 + \frac{A}{ab}\frac{\sigma_y}{p_{cr}^*} + \frac{atA}{2J}\frac{w_0}{a}\right)\left(\frac{p_y}{p_{cr}^*}\right) + \left(\frac{A}{ab}\frac{\sigma_y}{p_{cr}^*}\right) = 0 \tag{9}$$

The value for this geometric correction parameter should be determined from another type of experiments. A convenient choice is to take results from crushing tests. A theoretical alternative for this would be a 3D FEA.

Crushing

As shown in [5], for a general number n of identical, radial, equally spaced and concentrated loads of magnitude P applied on the ring, the nondimensional load parameter takes the form,

$$\lambda_n = \frac{n}{2\pi}\frac{Pa^2}{EJ} . \tag{10}$$

If a crushing experiment is considered simply modeled with two concentrated loads of magnitude P, diametrically applied (n=2), the nondimensional load parameter is, therefore,

$$\lambda_2 = \frac{1}{\pi}\frac{Pa^2}{EJ} . \tag{11}$$

On the other hand, it can be shown, [5], that for two concentrated loads, *in the linear range*, the diameter contraction occurring in the loading (vertical) direction may be approximated by

$$\frac{\Delta D_V}{a} = -0.1488\pi\lambda_2 . \tag{12}$$

Likewise, the diameter expansion occurring in the perpendicular (horizontal) direction may be approximated by,

$$\frac{\Delta D_H}{a} = 0.1366\pi\lambda_2 \tag{13}$$

Note that a general result, considering n identical, radial, equally spaced, concentrated (or distributed) loads, as shown in [5], might be incorporated. However, this would complicate the model with no assurance of any significant improvement. Sticking with the simpler analytical reasoning, the two concentrated crushing load model is then applied.

Therefore, given a particular carcass, the geometric correction parameter may be then determined from crushing experiments, by the following four simple steps procedure:

1. Take the average (nondimensional) $\Delta D_V/a \times \lambda_2$ curve from various tested samples;
2. Determine the inclination $(m_V < 0)$ of the straight line that best fits the linear part of this average curve;
3. From Eq. (12) determine the geometric correction factor as:

$$K = -\frac{0.1488\pi}{m_V} . \tag{14}$$

4. For consistency verification purposes, the line $\frac{\Delta D_H}{a} = \frac{0.1366\pi}{K}\lambda_2$ may be then compared with the linear part of the mean, experimental, horizontal diameter expansion curve, $\Delta D_H/a \times \lambda_2$.

The finite element model

Wet Collapse

The wet collapse numerical model considers the full geometry of the carcass profile. The only geometric assumption of this model is that the carcass pitch effect can be neglected in the study of the collapse problem. In the model, the carcass layer is considered as formed by a set of rings with the same cross section as the real carcass profile.

A 3D mesh is generated using the element SOLID185 (first order solid, with 8 nodes and three degrees of freedom per node). Figure 5 shows the 3D model with the carcass and the adjacent polymeric layer.

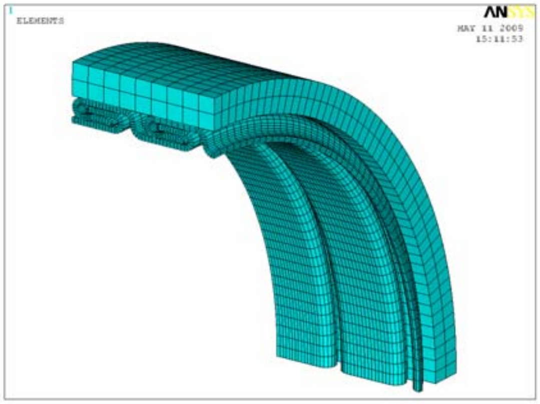

Figure 5 - Wet collapse model mesh (in this study, the 2.5" carcass model has 56,328 nodes and the 4.0" has 64,803 nodes)

To represent the carcass kinematics through an infinite sequence of rings, the coupling between degrees of freedom shown in green in Figure 6 need to be considered. The boundary conditions considered in the model are shown in Figure 7 and Figure 8. The two symmetry planes are taken into account, so only ¼ of the geometry is considered.

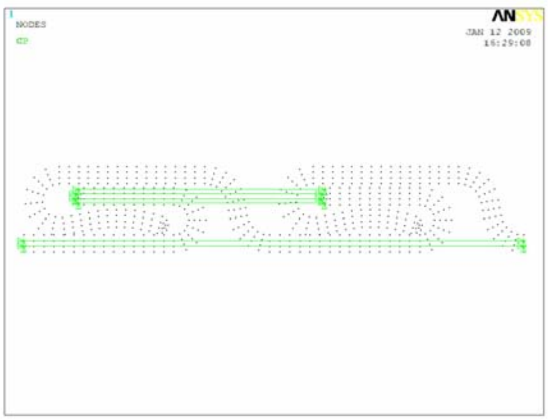

Figure 6 - Degrees of freedom coupling

The boundary conditions applied to the internal plastic layer include an axial restriction, since a close to plane strain state would occur for this layer. These conditions are shown in Figure 8.

The only load considered is the external pressure, applied on the polymeric layer surface (Figure 7). Loading is transmitted to the carcass through the contact between the two layers.

Contacts between internal carcass layer surfaces are modeled as frictionless. Furthermore, material nonlinear behavior and geometric nonlinearities are taken into account. Once the collapse of carcass is a snap-through like problem, for capturing the exact collapse curve it is necessary to use an arc-length procedure, and not only a simple Newton-Raphson method.

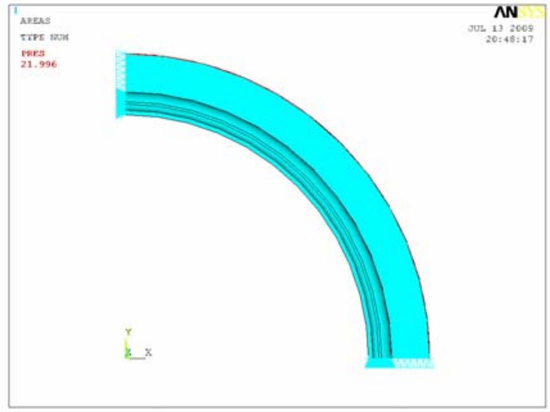

Figure 7 - Boundary conditions for wet collapse model (applied to the carcass layer and internal plastic layer)

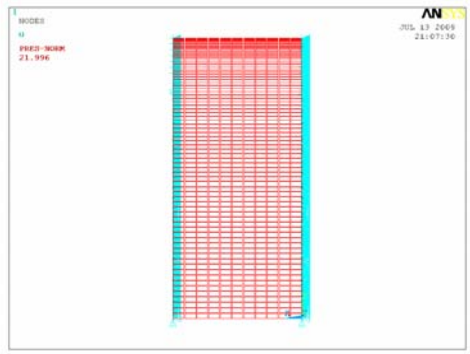

Figure 8 - Boundary conditions for wet collapse model (applied to the internal plastic layer condition)

The present wet collapse model can take into account the initial ovalization of the carcass layer. This parameter influences the collapse prediction, once the larger the initial ovalization, the smaller is the collapse pressure.

Ovalization, according to API 17B definition, [7], is given by:

$$e = \frac{(D_{max} - D_{min})}{(D_{max} + D_{min})} \tag{15}$$

Sensibility tests were made by varying the initial ovalization value. There is a significant difference between collapse values predicted with different initial ovalization values, reaffirming the importance of this parameter. That study showed that manufacturing differences can affect experimental results significantly. For the present analyses, an initial ovalization of 0.2% was assumed.

The carcass material is modeled as non-linear elastic-plastic. The evaluation of a correct stress-strain curve is a difficult task. Due to the metal conformation, during the carcass manufacturing process, strain hardening may occur, modifying significantly the yield stress. The assessment of a representative yield stress value for the carcass layer material was done using the procedure described below in the crushing load model. The resulting curve is shown in Figure 9.

The Young modulus of the carcass material is 192,500 MPa and its Poisson ratio is 0.3. As one can see in Figure 9, a proper proportionality limit for the carcass steel is 600 MPa. The second slope of the steel material is assumed to hold up to 2,000 MPa. Plasticity is modeled as bi-linear, with kinematic hardening.

The polymeric layer material is modeled as nonlinear elastic. The main effect of the polymeric layer in the model is to transmit the external pressure loading to the carcass.

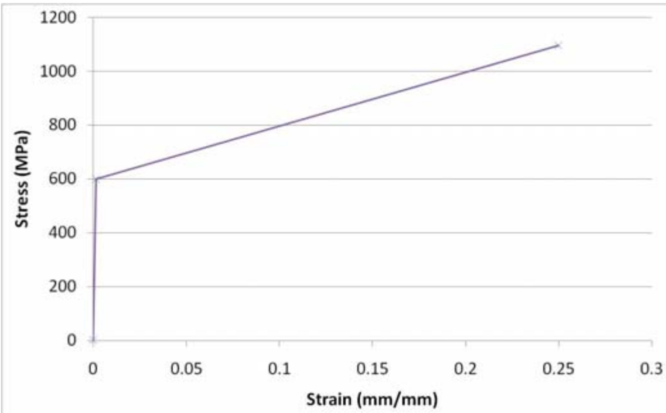

Figure 9 – Stress-strain curve for the carcass material

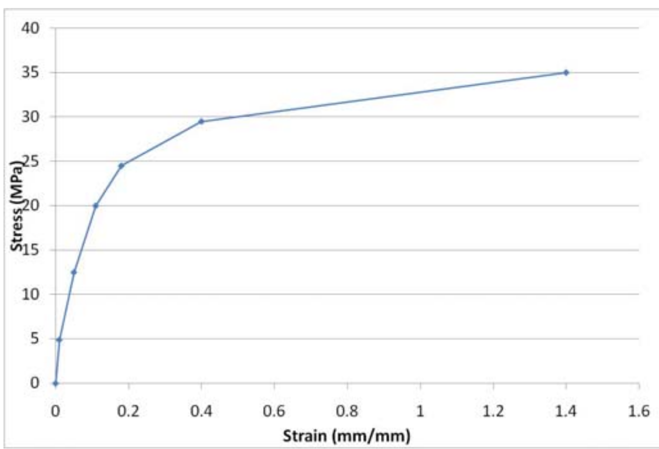

Figure 10 – Stress-strain curve for the polymeric layer material

Crushing

The finite element model for crushing tries to represent the conditions physically tested. Figure 11 shows the geometry used in the model. Both the interlocked carcass and the adjacent plastic layer were included.

The assumptions concerning the carcass and the internal polymeric layer, the materials and the meshes are exactly the same taken in the wet collapse model except for the symmetry (1/4 of geometry is considered in the collapse model and only 1/2 geometry is considered in the crush model). In the crushing model, there is no external pressure loading. Two blocks illustrated in Figure 11 provide a pair of directly opposite forces.

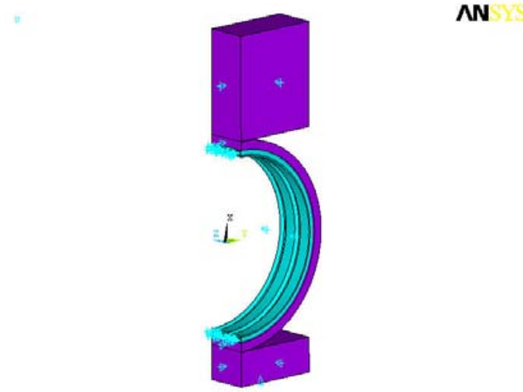

Figure 11 – Geometry of the model and the considered boundary conditions; [8].

A vertical displacement is imposed on the upper face of the larger block, step by step, as in the experiment. The lower block is fixed. This procedure tries to simulate the experiment. More details about this model can be found in [8].

The stress-strain curve of the carcass steel was parameterized in the yield stress value, using as a base of reference the mean experimental stress-strain curve for the non-manufactured material.

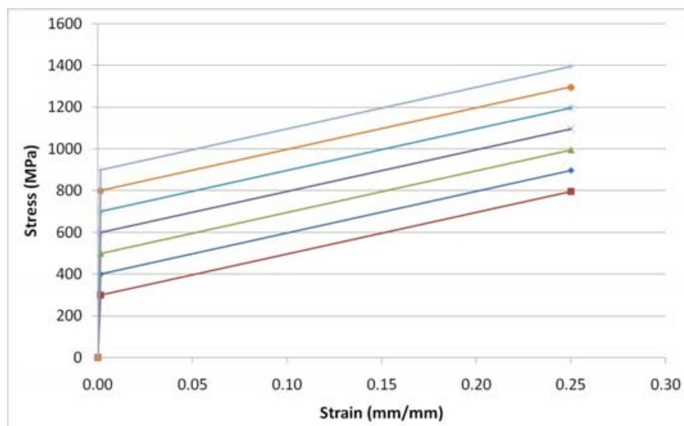

Figure 12 – Material curves for different manufacturing stress values

It is possible to construct a set of curves, each one assuming a different stress value that would be achieved in the manufacturing process. For this procedure, one can assume that the strain recovery curve after unloading is parallel to the first linear portion of the material curve. This procedure is described, for example, in [9]. The maximum stress achieved in the manufacturing process will be the new yielding stress of the material. Practically, the Young Modulus does not change, but the material becomes harder and supports, elastically, a larger value of stress.

Figure 12 shows the obtained curves, for different achieved levels of stresses, resulting in different new yielding stress values. All these curves have the same slope, in their first and second portions. The only difference between them is the yielding stress, assumed to be the exact value of the slope transition.

The objective of the crushing model here presented is to find the material curve that provides a best fit between the experimental crush test and the numerical model.

THEORETICAL-EXPERIMENTAL COMPARISON

Crushing

The numerical model was run considering the stress-strain curves presented in Figure 12. The resulting load vs. diameter variation were plotted for all cases and compared to the respective experimental mean curves, for both carcasses. Both, horizontal and vertical diameter variations were taken into account. For this parametric analysis the best fit led to a yield stress of 600MPa. This value was then taken as the yield stress for the collapse results comparison. Further discussion on the fitting procedure is outside the scope of the present work.

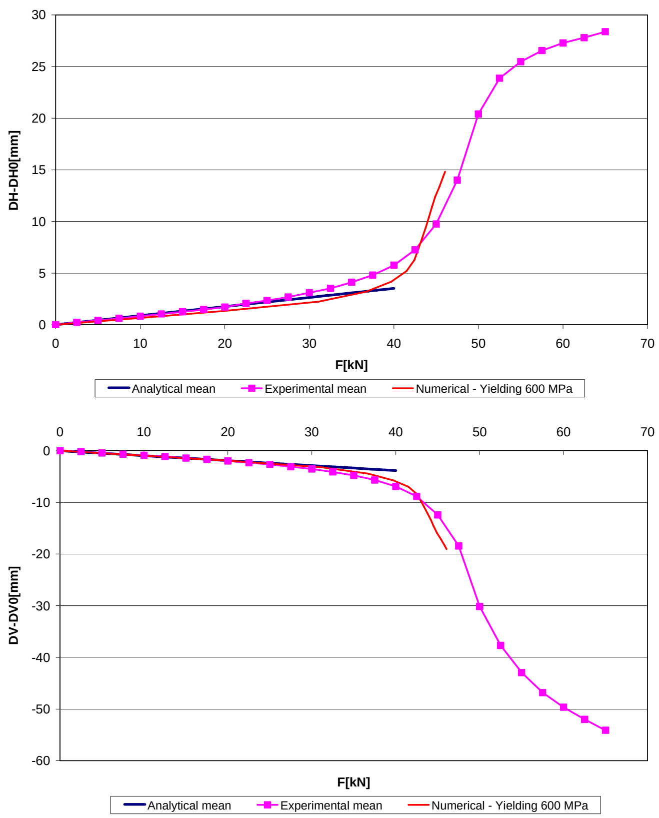

Figure 13 – Crush results for the 2.5"carcass – horizontal and vertical diameter variations. Analytical, numerical and experimental curves.

For the analytical results, the geometric correction factor K was determined from experiments, taking the values of 0.409 and 0.562 for the 2.5 and the 4in samples, respectively. The value of 600MPa was applied in the simple yielding criterion adopted.

Figure 13 and Figure 14 shows comparisons between analytical, numerical and experimental results. An average filling factor (0.82) was used. The results are encouraging. Parametric analyses considering the filling factor were also carried out but are not presented, for conciseness sake.

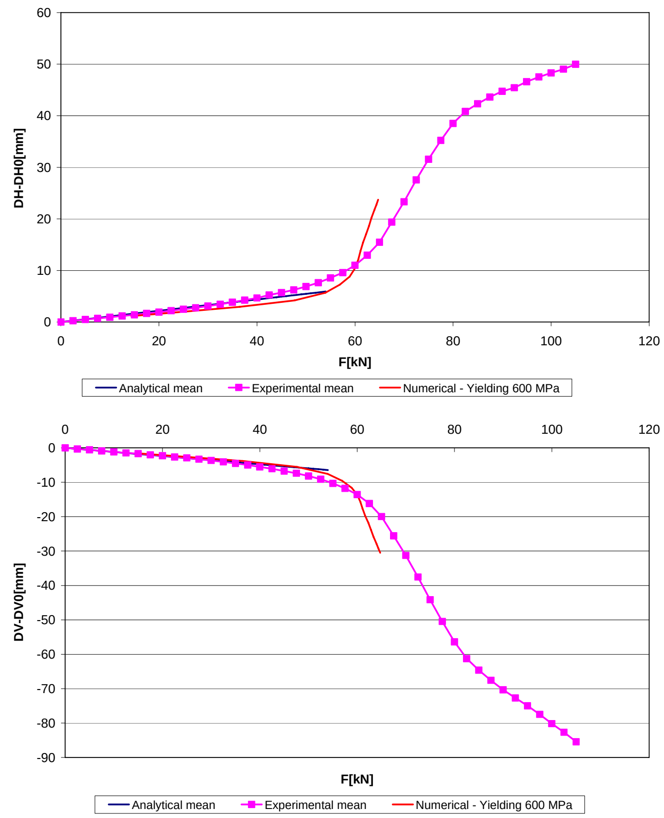

Figure 14 – Crush results for the 4"carcass – horizontal and vertical diameter variations. Analytical, numerical and experimental curves.

Wet Collapse

Table 3 shows the numerical predictions for collapse, compared with the experimental values. Collapse curves obtained with the numerical model are shown in Figure 15 and Figure 16.

Table 4 shows the results of a sensitivity analysis obtained with the analytical model, by varying the initial ovalization.

Finally, Table 5 presents the results of a best-worst case scenario analysis, obtained through the analytical model, by varying the internal diameter (ΔID) and the filling factor (ψ) .

The collapse pressure values for the 'worst case' scenario (9.22 and 6.01MPa) agree fairly well with the corresponding experimental lower bound ones (9.52 and 6.67MPa). On the other hand, the values for the 'best case' scenario (12.39 and 8.07MPa) agree satisfactorily with the average value (13.33MPa), for the 2.5 in pipe and very well with the upper bound value (8.05MPa) for the 4in pipe.

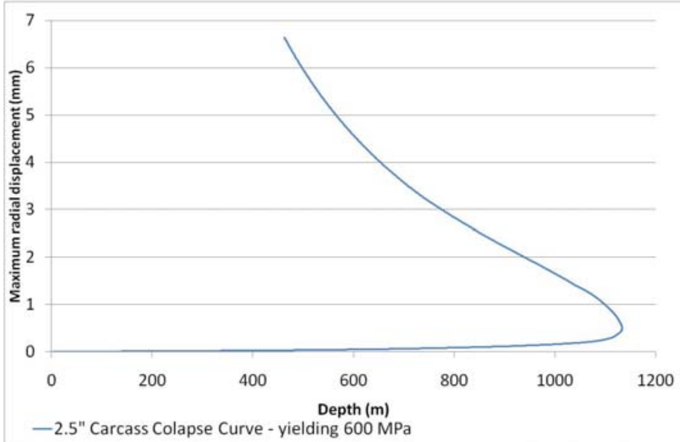

Figure 15 – Maximum radial displacement (mm) for the 2.5"diameter carcass

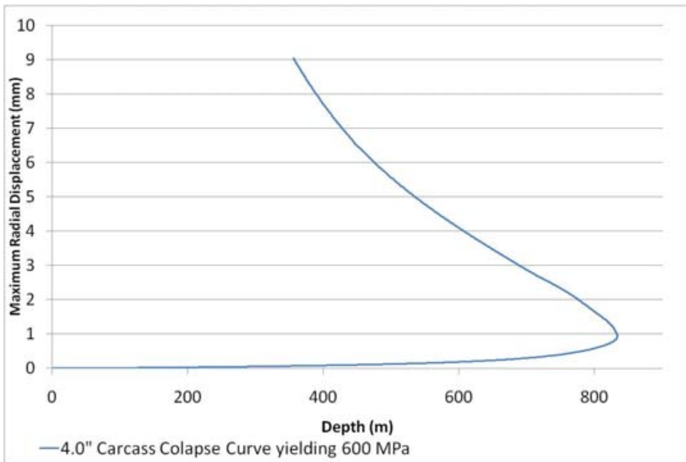

Figure 16 – Maximum radial displacement (mm) for the 4.0"diameter carcass

Table 3 – Numerical vs experimental values

Collapse Pressure [MPa]	Numerical	Experimental
2.5in	11.39	13.33 ± 3.81
4in	8.38	7.36 ± 0.69

Table 4 – Analytical results as function of initial ovalization

Ovalization (%)	2.5in	4in
0.00	11.29	7.36
0.10	11.01	7.18
0.20	10.76	7.01

Table 5 – Collapse Pressure [MPa]. Analytical Model.
$\sigma_y = 600\text{MPa}$ **;**

Best scenario: $\Delta ID = -1\%$ **;** $\psi = 0.94$ **; no ovalization.**

Worst scenario: $\Delta ID = +1\%$ **;** $\psi = 0.60$ **; ovalization: 0.2%**

Case	2.5in	4in
Best	12.39	8.07
Worst	9.22	6.01

CONCLUSIONS

A theoretical-experimental methodology analysis considering analytical and numerical modeling together with experimental procedures was presented for the study of wet collapse failure mechanism of flexible pipe carcasses.

The simple analytical model is based on equivalent ring assumptions. The 3D non linear finite element model considers the carcass as formed by a set of rings with the same cross section as the real carcass profile.

A comparison of simple crushing experiments with parametric numerical simulations was used to obtain a representative value for the yielding stress of the conformed carcasses. The same crushing experiments were also used to adjust the simple analytical equivalent ring model.

A theoretical-experimental methodology was then constructed to deal with the prediction of the wet collapse. Further work will include the effect of pressure armors.

ACKNOWLEDGMENTS

This work is a partial results of the Prysmian/USP project "Flexible Pipe: Prototype Development and Qualification Programs; Phases 1 and 2". FAPESP and CNPq, respectively the State of São Paulo and the Brazilian National Research Agencies, are acknowledged.

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