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CRUSHING TESTS OF FLOWLINES INTERNAL LAYERS: AN EXPERIMENTAL APPROACH VIA OPTICAL MOTION CAPTURE AND IMAGE PROCESSING

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ABSTRACT

New optical measurement approach for crushing tests of flow lines internal layers is detailed, based on an accurate tracking of the deformed carcass section through image processing. The results are compared to those from standard procedures based on discrete measurements using calipers. The new approach shows to be not only appropriate for the standard measurement requirements but also enables a comprehensive understanding of the crushing behavior.

NOMENCLATURE

CC	correlation coefficient
DH	horizontal diameter
DH_0	horizontal diameter at the initial instant
DV	vertical diameter
DV_0	vertical diameter at the initial instant
F	force
Z	vertical position of the marker

1. INTRODUCTION

A design methodology for flexible pipes flow lines has been developed, regarding global and local structural analysis, flow assurance and gas permeation issues, material selection and fabrication processes, as well as installation and reliability. A number of tests was carried out concerning the investigation of specific failure modes.

Collapse and crushing of the internal carcass are some of the numerous failure modes addressed. Among the experimental procedures, simple crushing tests may be a quite useful source of theoretical and practical information for the local structural analysis models. Besides, such tests provide specific data on plastic deformation of the carcass and its implications in establishing limit loads for the laying operation, as well as in eventual pigging inspection. In this context, the present paper addresses a new experimental approach. Such an approach applies an accurate position tracking and stereoscopic image processing method. The methodology is described in the text and applied to a 4-inch flexible pipe carcass case.

Comparison with standard measurements technique shows the accuracy of the proposed method.

A companion paper [1], in the same Conference, presents theoretical-experimental comparisons using the set of experimental data obtained by the proposed method.

2. EXPERIMENTAL METHODOLOGY

The following sections describe the materials, experimental bench and methods applied for the crushing tests.

Experimental bench and samples

The crushing tests were carried out according to Technical Communication TC-01, [2]. The experiments were performed at the Laboratory of Structures and Structural Materials at Escola Politécnica, University of São Paulo.

All the tests were performed by using a standard reaction rig with maximum load capacity of 105kN, proper for mechanical tests, taking into account load or displacement control. Figure 1 depicts the equipment. Load control strategy was applied, the resulting displacements were acquired by means of an analogical output of ±10V, compatible with the acquisition system utilized. The equipment presents nominal precision of 0.1mm, which was verified through a complementary displacement transducer.

Figure 1 – Standard reaction rig for mechanical tests: maximum load capacity of 105kN.

Due to the reduced dimensions of the support table in the testing rig, it was necessary to arrange the samples according to the setup presented in Figure 2, i.e., confined between the support table and a loading beam of large bending stiffness. With this arrangement, the machine table supported the sample whereas the upper beam applied the compression load. This assures the loading is applied uniformly. In order to comply with these requirements, the beam should have the same length or be larger than the lengths of the samples. It should also have a large enough bending stiffness so as to act practically as a non-deformable body. A classic beam on elastic foundation model was applied to properly address this requirement; details are shown in reference [2].

Samples of two distinct carcasses, with 2½" and 4" internal diameter, were tested under compression (three samples of each). However, for conciseness sake, only the 4" samples results are presented here. The whole set of results can be found in reference [3].

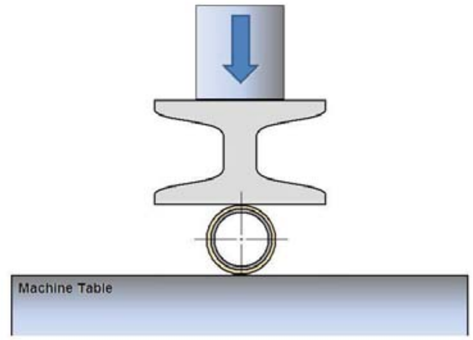

Figure 2 – Schematic arrangement for compression load application.

It should be remarked that the prototypes constructed for testing were not yet assembled with pressure armor. Thus, the nucleus of the flowline was composed solely by the carcass and the pressure plastic layer. Table 1 presents the main characteristics of the 4" samples tested.

Table 1 – Main characteristics of the 4" samples.

Samples of 4"	***Dimensions***
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 layer [mm]	5

* Only the annular composed by carcass and pressure layer.

The lengths were defined considering two main aspects: the limitation of the maximum possible load of the equipment available for the tests and the minimum dimension to avoid end effects (measured in terms of specific parameters). In this case, the length definition was guided by numerical FEM simulation, complemented by analytical modeling.

Experimental methods

As mentioned, two experimental methods were adopted, both described below. Before that, it is important to emphasize that the standard method is extensively applied and accepted for design methodology of flow lines, naturally making it a reference for alternative methods such as the one proposed herein, by using optical tracking and image processing.

<u>Standard method via calipers</u>:

Apart from some minor variation, the standard method via calipers is always based on a procedure that covers the following steps:

- Sample preparation by cutting it in a defined length and treating its edges (finishing, cleaning of the burrs);
- Definition of the reference points for measurement via caliper. In this case, four points of the sample were

symmetrically distributed in the perimeter, defining the vertical (DV, distance between points 1 and 3) and horizontal (DH, distance between points 2 and 4) directions. See Figure 3;

- Measurement of the initial dimensions in vertical and horizontal directions on the carcass surface, respectively DV_0 and DH_0;
- Sample installation at the test machine, by assuring alignment and level along the length;
- Application of the compression loads by steps.

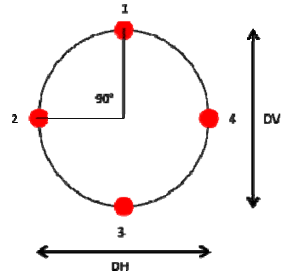

Figure 3 – Distribution of reference points and main directions adopted for the method via calipers.

The compression load was increased by steps of 2.5kN, starting from 0 to 100kN, the machine limit. For each step, after waiting for structural accommodation, the following actions were carried out. First, the vertical and horizontal dimensions were measured by two distinct operators, each one with distinct calipers. Simultaneously, the values of applied loads and displacements (by means of a LVDT which was installed to the beam) were automatically registered using a standard Acquisition Data System – ADS. This procedure was performed for all samples.

Alternative method via optical motion capture:

By means of image processing, this procedure is able to track some passive markers placed in a convenient position at the samples.

Figure 4 – One of the two special cameras used by de optical motion capture.

The system allowed to continuously monitor the markers positions, with good precision and high sampling frequency, 10Hz. Figure 4 shows one of the cameras used by the optical motion capture (a minimum of two cameras is necessary for stereoscopy).

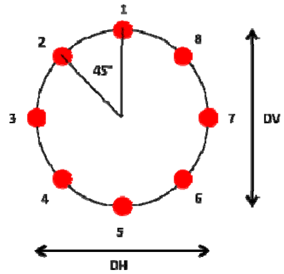

Figure 5 – Distribution of marker positions and main directions adopted for the method via optical motion capture.

Some specific adaptations were necessary as discussed in the following preparation procedure.

First, the samples were prepared, complying with:

- Internal black painting in order to avoid light reflection;
- Measurement of the sample circularity; diameters 1-5, 2-6, 3-7 and 4-8, indicated in Figure 5. The horizontal initial internal diameter DH_0 refers to the distance between points 3 and 7. Likewise, the vertical initial internal diameter, DV_0, refers to the distance between points 1 and 5;
- Reflexive markers on the sample perimeter were placed: internally, to measure the variation of the metallic carcass diameter (use of metallic device) and externally, on the plastic cover to measure the diameter variation of the plastic cover diameter, see Figure 6a.

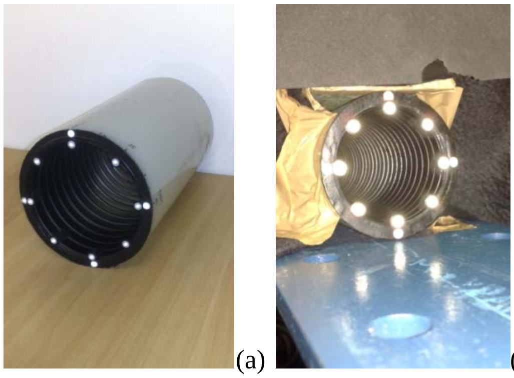
(a) (b)

Figure 6 – (a) Reflexive markers implemented to the cross section perimeter, (b) Calibration sequence.

After that, the samples were placed at the machine for mechanical tests. This step was performed considering the correct alignment of the samples. As shown in Figure 6b, a complementary sequence of calibration steps was performed.

3. RESULTS AND DISCUSSION

The results concerning the ovalization measured through both caliper and optical motion capture methods are presented in this section. Those refer to the variation of the horizontal and of the vertical diameters of the 4'' sample subjected to the compression loads. The results of variation, ($DH - DH_0$) and ($DV - DV_0$), are presented in Table 2. According to the proposed procedure, the results concern the mean values between three samples.

Table 2 – Comparison between mean results for the 4" samples (horizontal and vertical) from caliper and image.

F [kN]	*Via Caliper*		*Via optical motion capture*	
	$DH - DH_0$ [mm]	**$DV - DV_0$ [mm]**	**$DH - DH_0$ [mm]**	**$DV - DV_0$ [mm]**
0.15	0.00	0.00	0.01	0.00
2.47	0.24	-0.32	0.87	-1.05
4.96	0.50	-0.58	1.21	-1.54
7.46	0.71	-0.89	1.42	-1.83
9.95	0.93	-1.18	1.61	-2.08
12.45	1.18	-1.46	1.79	-2.24
14.95	1.39	-1.68	1.95	-2.52
17.44	1.67	-2.02	2.14	-2.76
19.94	1.93	-2.28	2.34	-2.98
22.43	2.22	-2.64	2.56	-3.32
24.93	2.48	-2.91	2.81	-3.54
27.42	2.75	-3.28	3.07	-3.89
29.92	3.10	-3.65	3.34	-4.29
32.42	3.45	-4.07	3.64	-4.63
34.91	3.85	-4.52	3.93	-5.05
37.40	4.24	-4.98	4.21	-5.48
39.90	4.67	-5.52	4.53	-5.98
42.39	5.26	-6.06	4.86	-6.51
44.89	5.71	-6.75	5.26	-7.13
47.38	6.23	-7.38	5.70	-7.78
49.89	6.88	-8.18	6.15	-8.59
52.39	7.63	-9.13	6.66	-9.47
54.88	8.55	-10.31	7.26	-10.55
57.38	9.59	-11.77	8.06	-11.92
59.87	11.00	-13.58	9.22	-13.61
62.37	12.96	-16.19	10.76	-15.88
64.86	15.48	-19.97	12.94	-18.94
67.36	19.39	-25.56	15.79	-23.17
69.86	23.31	-31.27	18.97	-28.06
72.34	27.56	-37.54	22.39	-33.28
74.84	31.56	-44.14	26.11	-39.20
77.33	35.21	-50.46	29.56	-44.89
79.82	38.51	-56.41	32.62	-50.21
82.31	40.82	-61.28	35.07	-55.35
84.80	42.32	-64.60	36.90	-59.74
87.30	43.62	-67.57	38.25	-63.36
89.79	44.74	-70.33	39.21	-66.23
92.28	45.43	-72.73	39.96	-68.69
94.77	46.60	-74.99	40.65	-71.01
97.25	47.52	-77.46	41.27	-73.26

The plots in Figure 7 present the horizontal diameter variation as a function of the applied loads from caliper measurements. It is clearly seen that the ovalization behavior of the pipe samples presents a great repeatability, even for elasto-plastic regime region. The same analysis procedure was applied to the vertical ovalization of the samples, see Figure 8.

By means of image processing, the optical motion capture method is capable of tracking the passive markers placed in a convenient position at the samples. The system allows to continuously monitor the markers positions, with good precision and high sampling frequency. Figure 9 presents the comparison between the results obtained from caliper and optical motion capture.

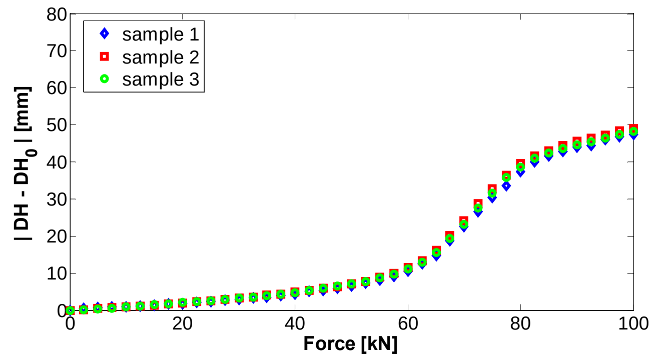

Figure 7 – Horizontal diameter variation of three distinct samples of the 4" pipe from caliper measurements.

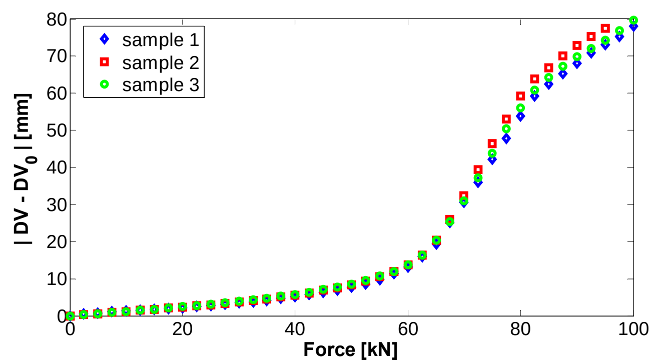

Figure 8 – Vertical diameter variation of three distinct samples of the 4" pipe from caliper measurements.

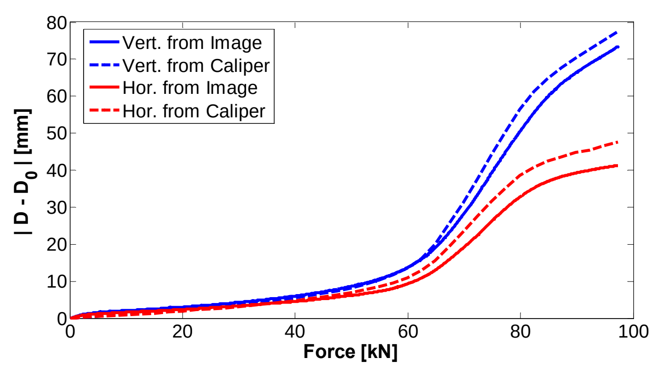

Figure 9 – Comparison between diameter variation measurements from caliper and optical motion capture.

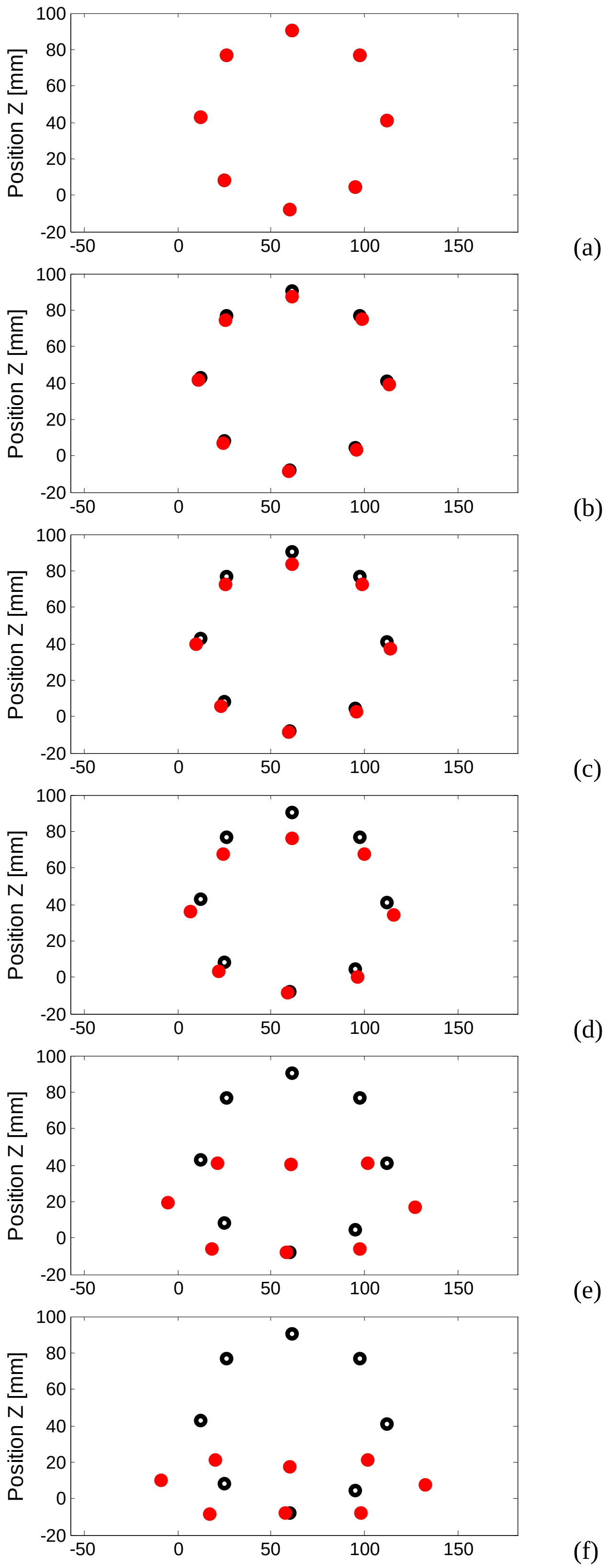

Figure 10 – Examples of results from optical motion capture for steps: (a) 0; (b) 20; (c) 40; (d) 60; (e) 80; and (f) 100kN.

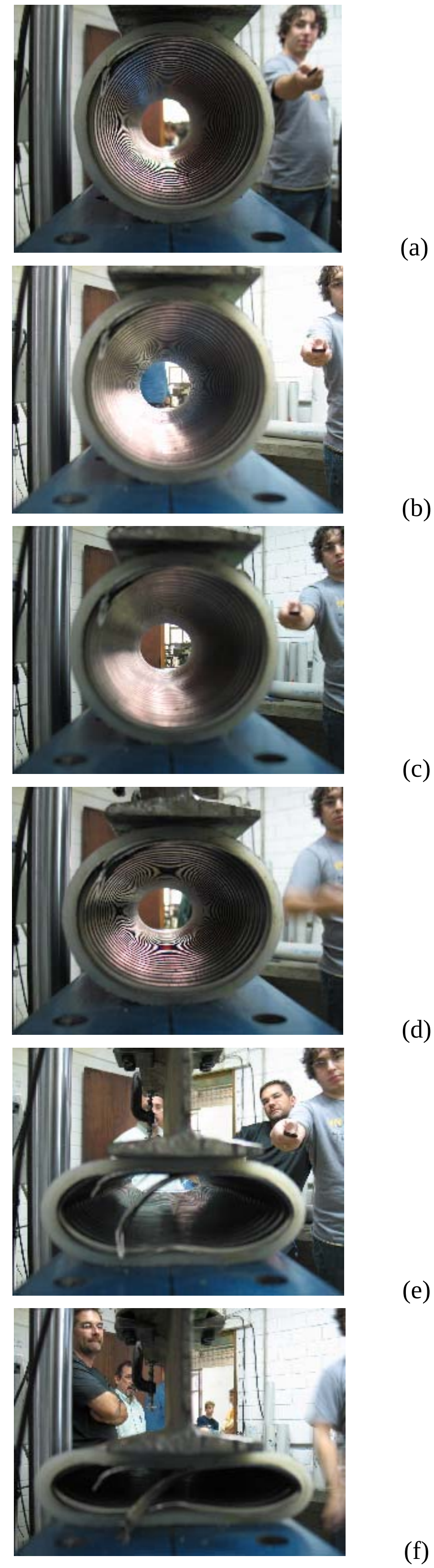

Figure 11 – Examples of sample pictures for steps: (a) 0; (b) 20; (c) 40; (d) 60; (e) 80; and (f) 100kN.

As a result, graphics for each nominal applied load were plotted and presented together with the respective picture of the sample cross section. Figure 10 and Figure 11 show examples of step measurements from optical motion capture. The steps represent different force levels: 0, 20, 40, 60, 80 and 100kN. The black circles are the initial position of the markers, and the red circles are the new position of the targets in the correspondent force level. Figure 12 summarizes the step by step cross section deformation for a 4” pipe sample, from 0 to almost 100kN.

Comparison between all the results obtained from both methods, Figure 7, allows verifying the good agreement, in this case, quantitatively confirmed by means of the cross-correlation coefficients:

$CC_{\text{calliper, optical}}\ (DH - DH_0) = 0.9992;$
$CC_{\text{calliper, optical}}\ (DV - DV_0) = 0.9993.$

Those results confirm the optical motion capture with image process as a reliable method for crushing tests, taking into account not only the precise measurement of the typical results but also the continuous monitoring of the crushed cross section, as those exemplified by the Figure 12.

Note that the measures obtained with the standard procedure tend to be different from the ones obtained with the optical procedure for higher crushing loads (see Table 2 and Figure 9). For lower loads, these measures are almost coincident, but for higher ones, differences up to 15% are observed. In fact, at high loads, larger than 60kN, the carcass starts unlocking at the sample cut, turning the caliper measurement not accurate; see pictures (e) and (f) in Figure 11. This reveals another advantage of the optical system.

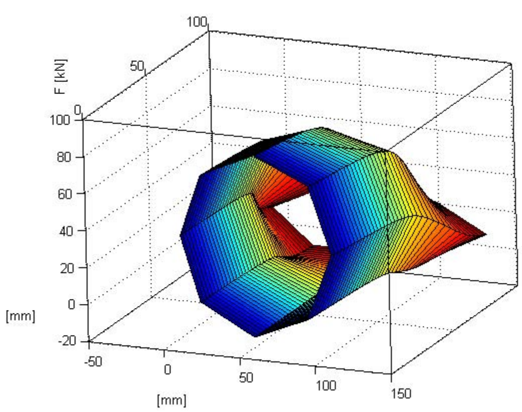

Figure 12 – Step by step during the crushing test of the 4” pipe sample.

Finally, in order to determine the load corresponding to the linear behavior limit, the following procedure was elaborated, based on the horizontal and vertical variation plots:

- First, a set of successive linear regressions is obtained using an increasing number of points taken from the sample ovalization (e.g. $DH - DH_0$ vs. F[kN] and $DV - DV_0$ vs. F[kN]). The R-square correlation value (R^2) for each sequence of points (from 5 to 15) is plotted against the load of the last point;
- The mean curves R^2 vs. F [kN] are plotted for horizontal and vertical variations and contrasted with a chosen value, attributed as a criterion of linearity measure (e.g. 99.5%);
- According to Figure 13, a 30kN load linearity limit is found from the horizontal diameter variation mean curve, corresponding to $R^2 > 99.5\%$. Consistent to the horizontal behavior, the same result of linearity was also observed for the vertical ovalization, see Figure 14.

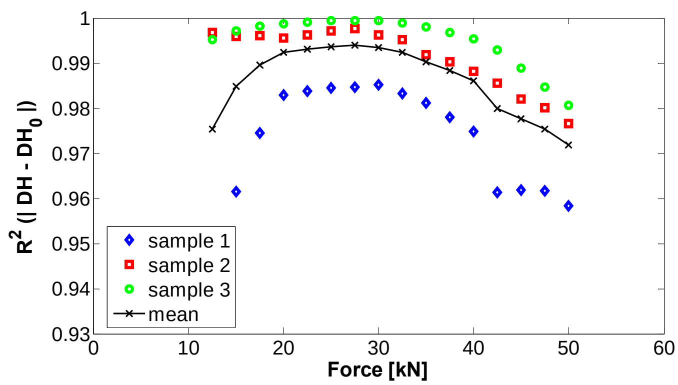

Figure 13 – Linear correlation: determination of the linearity limit for the 4” pipe; horizontal diameter variation.

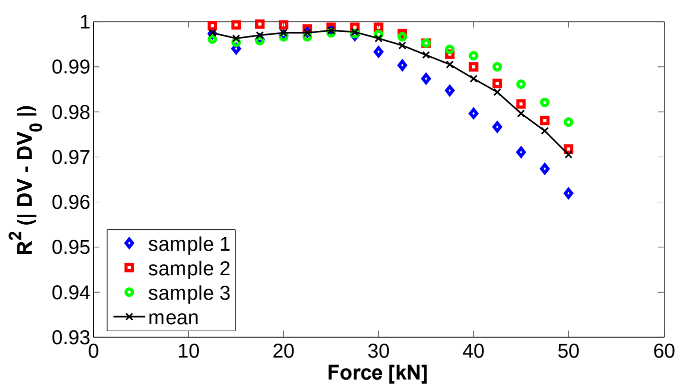

Figure 14 – Linear correlation: determination of the linearity limit for the 4” pipe; vertical diameter variation.

As a matter of fact, the optical procedure may be equally applied to the inner carcass or to the internal plastic layer. Figures 15 and 16 illustrate such a feature. Note that at high loads the plastic layer detaches from the inner carcass, as a classical plastic instability is revealed in an eight-shaped form; see Figure 11 (e; f).

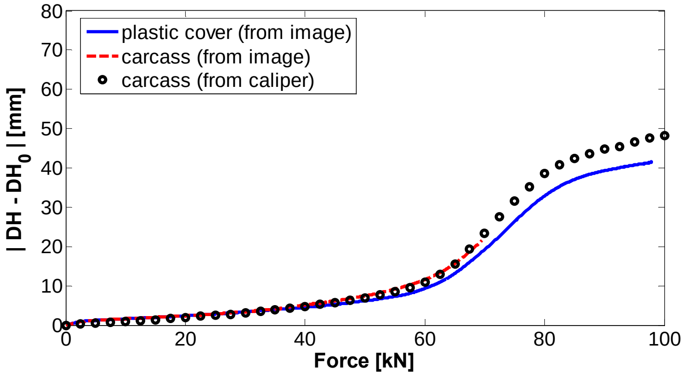

Figure 15 – Horizontal diameter variation measurements made on the plastic cover and on the carcass for the 4” pipe.

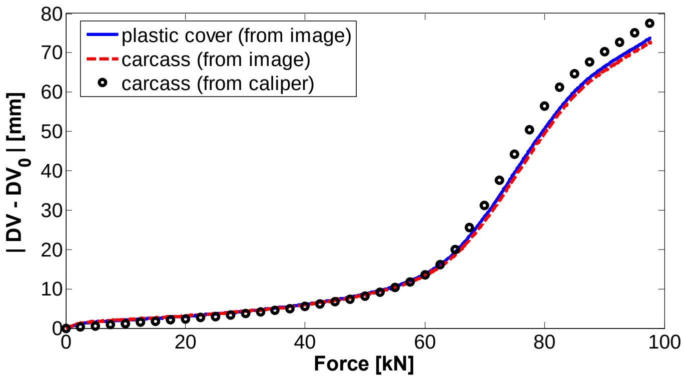

Figure 16 – Vertical diameter variation measurements made on the plastic cover and on the carcass for the 4” pipe.

4. CONCLUSIONS

This paper presented experimental results from crushing tests with the flow portion of a 4” ID flexible pipe, composed by a carcass constrained by a cylindrical extruded pressure layer.

By means of a standard procedure, via calipers, mean curves (from 3 samples) of the horizontal and vertical diameter variation were obtained. A limit value of 30kN was observed for the linear regime, with great repeatability.

As an alternative procedure, an optical motion capture system was used, with a proper sample preparation and passive (reflexive) markers distributed along the sample perimeter. This procedure not only allowed a practically continuous monitoring of the crushing, but also confirmed the results obtained via the standard procedure via calipers.

The comparisons between both methods showed the quality of the results and attested the optical motion capture as a good alternative for this kind of tests, with an extra feature: the possibility of a practically continuous monitoring of the cross section geometry under progressive compression load.

The results herein presented are part of an extensive research regarding the development of a design methodology for flow lines and risers and they have been strongly useful for theoretical validations, as those presented in reference [1].

ACKNOWLEDGMENTS

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