EXPERIMENTAL RESULTS REGARDING THE INFLUENCE OF INITIAL OVALITY ON LOCAL BUCKLING UNDER EXTERNAL PRESSURE (COLLAPSE) OF OIL INDUSTRY TUBULARS

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1 INTRODUCTION

One of the most important loads which can decisively affect the resistance capacity of oil industry tubulars is the external hydrostatic pressure. Under the effect of such pressure, often combined with tensile and/or bending loads, the local buckling phenomenon can occur leading to pipe ovalisation. When the external pressure is acting alone, this phenomenon is called collapse. Such phenomenon is of crucial importance for casing and tubing (mostly in high pressure wells), and for submarine pipelines during the installation phase (when the pipeline is empty), especially in deep waters.

The collapse resistance capacity of pipes for casing, tubing and sealines is importantly affected by some factors, among which the pipe geometrical imperfections (mainly its initial ovality), the pipe material anisotropy, and the level of residual stress.

In such context, the research activities described in this paper aimed to investigate the influence of the pipe initial ovality on the external pressure collapse phenomenon by performing some tests on small scale models, based on the similitude law. These tests followed other tests performed to investigate collapse for perfectly circular tubes, presented in a previous paper. In addition, a future research activity aims at studying the influence of the pipe material anisotropy, of the level of residual stress, and also the effect of tensile and bending loads on the local buckling phenomenon for tubulars.

2 REVIEW OF PREVIOUS RESULTS REGARDING THE INFLUENCE OF PIPE INITIAL OVALITYON THE COLLAPSE PHENOMENON FOR TUBULARS

Along the years, various researchers proposed a series of calculation formulas, based on theoretical models and/or test results, to evaluate the critical external pressure at collapse, p_c, and the influence – among others – of the pipe initial ovality upon this value.

These studies showed that the collapse mechanism differs with the value of the ratio between the pipe outside diameter and its wall thickness, D/t, as follows: for $D/t > 35$, collapse occurs by means of an elastic flattening; for $D/t<15...20$, collapse will take place in the plastic field; for $D/t = 20...35$, the pipe failure mechanism is much more complex, elastic-plastic.

In case of elastic collapse, the critical value of the external pressure (the elastic collapse pressure) is given by the equation [8]:

$$p_c = p_E = \frac{2E}{1-\nu^2} \cdot \frac{1}{(D/t)^3} \qquad (2.1)$$

where E is Young’s elastic modulus, and ν is Poisson coefficient.

In case of plastic collapse, if considering the thin-wall tubes theory, the critical pressure value (the plastic collapse pressure) can be calculated as follows:

$$p_c = p_F = 2\sigma_c \cdot t/D \qquad (2.2)$$

where σ_c is the minimum specified yield strength (SMYS) of the pipe material.

For the transition zone between elastic and plastic collapse (for D/t = 15...35), various equations have been proposed, firstly assuming a perfect tube, as in equations (2.1) and (2.2).

In reality, a pipe is never perfectly circular, but it is always affected by geometrical imperfections (especially ovality and eccentricity), and also by material anisotropy, residual stresses, etc. In addition, experimental results showed that a pipe initial ovality leads to an important decrease of the critical pressure value, especially for D/t = 20...30 (i.e. in the transition zone). As a consequence, many researchers proposed calculation formulas including the initial ovality, δ_0, and/or the pipe eccentricity, ξ. The relationships most used in current design practice are summarized in Table 1 [6]. All relationships included in the table include pipe ovality and some of them also the effect of pipe eccentricity (which has not been investigated in our tests, as it has been proven to be much less important than the effect of ovality).

Table 1. Formulas for Assessing the Critical Collapse Pressure of Pipes

No.	**Author**	**Year of Proposal**	**Calculation Relationship**
1	Timoshenko	1933	$(p_c - p_E)(p_c - p_F) = p_c p_E \cdot 1{,}5\ \delta_0 D/t$
2	de Winter	1981	$(p_c - p_E)(p_c^2 - p_F^2) = p_c p_E p_F \cdot \delta_0 D/t$
3	SHELL	1975	$\frac{p_c}{p_F} = \sqrt{\frac{1 + p_F^2 / p_E^2}{p_F^2 / p_E^2 + 1/g^2}}$, $g = \sqrt{1 + \left(\frac{\delta_0}{2} \cdot \frac{D}{t}\right)^2} - \frac{\delta_0}{2} \cdot \frac{D}{t}$

4	Langner	1983	$p_c / p_F = 1 + 10\delta_0 + 0,25\xi$
5	Tamano	1983	$(p_c - p_E)\,(p_c - p_F) = p_E\, p_F\,(8,08\ \delta_0 + 0,23\ \xi)$
6	Lohmeier	1973	$p_c / p_F = [1 + \delta_0/2 + {}^2/_3\delta_0\,(D/t - 1)]^{-1}$
7	Nishioka	1976	$p_c / p_F = (1 - \xi) / (1 + 1,5\ \delta_0\,D/t)$
8	Small	1977	$p_c / p_F = [1 - 0,135\delta_0 + ({}^2/_3 - 0,51\delta_0)\ \delta_0\,D/t]^{-1}$

If considering the recommendations of the different Codes used in oil industry, it can be observed that the most recent internationally recognized Code dedicated to submarine pipelines, i.e. “Det norske Veritas” OS-F101 [4], much used worldwide, and also by British Code BS 8010 [3] indicate the use of de Winter equation (Tab. 1, pos. 2), considering a minimum imposed value for the initial ovality of 0.5%.

In addition to the formulas shown in Table 1 above, we include a relationship specially developed for a conservative assessment of the critical collapse pressure for ovalised coiled tubing, named TF relationship [7]:

$$p_c^4 + 2(k_1 - 2k_2^2)p_c^2 + k_1^2 = 0 \qquad (2.3)$$

where the values of coefficients k_1 and k_2 are to be calculated with the equations:

$$k_1 = 2\ \sigma\ t_{min}\ p_{co0}\ /\ (D - t_{min}) \qquad (2.4)$$

$$k_2 = [k_1 + p_{co0}^2\ [1+1.5\ (D_{max}-D_{min})/t_{min}]]/2\ p_{co0}\,, \qquad (2.5)$$

in which p_{co0} is the critical collapse pressure for perfectly circular tubing, D_{max} is the maximum value of the tubing outside diameter, D_{min} its minimum value, and t_{min} the minimum wall thickness value of the coiled tubing.

3 EXPERIMENTAL RESULTS REGARDING THE INFLUENCE OF PIPE INITIAL OVALITY ON TUBULARS COLLAPSE

As it can be easily seen, in all equations presented above the critical pressure value, p_c, depends only on the D/t ratio, and therefore the similitude law can be applied to study pipe collapse. As a consequence, all tests have been performed on small diameter pipe specimens who can be considered small scale models of large diameter pipes. An especially build pressure testing facility has been used, which can develop a maximum hydrostatic pressure of 1000 bar.

The tests have been performed using 31 steel specimens, which were taken from seamless pipes. The main characteristics of these specimens are shown in Table 2.

Table 2 - Specimens Characteristics

No.	**Outside Diameter** [mm]	**Material***	**No. of specimens**	**Yield Strength** [MPa]	**Ultimate Tensile Strength** [MPa]
1	60	A	7	230	340
2	60	X 52	9	358	455
3	38	X 56	9	380	640
4	32	X 70**	6	482	552
*According to API classification for line pipe materials [2]; **Pipe for coiled tubing QT 700: QT = Quality Tubing; 700 = 700000 psi = 482 MPa – specified minimum yield strength [6].					

The pipe specimens made of X52 and X56 steels have been machined outside to obtain different values of the pipe wall thickness (and *D*/*t* ratio), while the specimens made of A and X70 steels have not been machined.

Afterwards, all specimens have been subject to a controlled ovalisation process – using a hydraulic press – in order to obtain different values of the pipe initial ovality. For all specimens, the initial ovality value has been calculated with the following relationship:

$$\delta = 2\cdot(D_{max}-D_{min})/(D_{max}+D_{min}), \qquad (2.6)$$

after measuring the specimens' outside diameter values in four points around its circumference.

In addition, after testing, the pipe specimens have been cut in the collapse zone, and the pipe eccentricity values have been determined, using the values of the wall thickness measured in eight points around the circumference. The specimens' eccentricity values have been found to be sufficiently low (under 0.2 %) in order not to have any practical influence on the critical collapse pressure value. Such conclusion is based on some calculations performed using the formulas from Table 1 (pos. 4, 5, and 7) which take into account the effect of pipe eccentricity.

The test results are summarized in Table 3 for pipe specimens made of A steel, in Table 4 for pipe specimens made of X52 steel, in Table 5 for pipe specimens made of X56 steel, and in Table 6 for coiled tubing specimens made of X70 steel.

Each table shows, for each specimen tested, the *D*/*t* ratio value, the initial ovality value, the critical collapse pressure value obtained during testing, and the collapse pressure values calculated by using all formulas from Table 1 and also the TF equation (2.3) – for pipe specimens made of A and X70 steels.

If comparing experimental test results with calculated values from Table 3, it can be seen that, for specimens made of grade A steel, the closest collapse pressure values to the tests data are obtained if using the equations proposed by de Winter (Table 1, pos. 2), by Lohmeier (Table 1, pos. 6), and by Small (Table 1, pos. 8). All other formulas give results rather different with respect to the test data. For practical design purposes, the recommended relationship is the one proposed by de Winter which in most cases leads to critical collapse pressure values smaller than test results. However, if a conservative evaluation of this value is needed, the equations proposed by Timoshenko (Table 1, pos. 1), and Nishioka (Table 1, pos. 7) should be used, even if such evaluation might be too conservative.

When analyzing Table 4, it can be concluded that, for specimens made of X52 steel, the closest collapse pressure values to the tests data are obtained if using the equations proposed by Timoshenko (Table 1, pos. 1), de Winter (Table 1, pos. 2), Nishioka (Table 1, pos. 7), and – to some extent – Shell (Table 1, pos. 3). All other formulas give results rather different with respect to the test data in most cases; the formula proposed by Tamano (Table 1, pos. 5), which has been developed especially for casing, gives negative values of the collapse pressure for pipe initial ovality values greater than about 1.0 %. For practical design, in order to obtain a conservative evaluation of the critical collapse pressure value, the classical relationship proposed by Timoshenko, which always gives values smaller than the test results, is recommended. However, if the desired scope is to optimize the wall thickness value in order to reduce material costs, the relationship proposed by de Winter could be used.

If comparing the data included in Table 5, it can be seen that, for specimens made of X52 steel, the closest collapse pressure values to the tests results are obtained if using the equations proposed by de Winter (Table 1, pos. 2), Timoshenko (Table 1, pos. 1), Nishioka (Table 1, pos. 7), and – to some extent – Lohmeier (Table 1, pos. 6) and Small (Table 1, pos. 8). The other formulas give results rather different with respect to the test data in most cases, and the Tamano formula (Table 1, pos. 5) leads again to negative values. For practical design purposes, the relationship proposed by de Winter is strongly recommended, as it always gives values smaller than test results, but rather close to them.

If analyzing Table 6, it can be concluded that, for coiled tubing specimens (made of X70), the closest collapse pressure values to the tests data are obtained if using the TF equation (2.3) and – to some extent – the equations proposed by Timoshenko (Table 1, pos. 1), and Nishioka (Table 1, pos. 7).

Table 3 - Test Results for A Steel Pipe Specimens with Initial Ovality

No.	D / t ratio	Initial Ovality (%)	Collapse Pressure Value (MPa)									
			Test Result	Timoshenko	de Winter	Shell	Langner	Tamano	Lohmeier	Nishioka	Small	TF
1	10.9	0.90	26.0	16.7	25.6	33.6	80.5	10.6	26.0	17.2	26.6	14.6
2	10.9	0.80	27.0	17.9	26.9	34.4	76.3	13.9	27.1	18.4	27.8	15.4
3	10.9	0.50	31.0	22.7	31.6	37.1	63.6	24.0	31.3	23.3	31.9	18.9
4	12.7	1.20	17.0	10.7	17.2	25.8	79.9	0.9	18.2	11.1	18.8	9.8
5	12.7	0.90	20.0	12.9	20.1	27.8	69.1	8.8	20.8	13.4	21.3	11.3
6	12.7	0.60	23.0	16.3	24.0	30.3	58.1	17.2	24.2	17.0	24.8	13.7
7	12.7	0.50	24.9	17.9	25.6	31.2	54.5	20.2	25.7	18.6	26.1	14.9

Table 4 - Test Results for X 52 Steel Pipe Specimens with Initial Ovality

No	D / t ratio	Initial Ovality (%)	Collapse Pressure Value (MPa)								
			Test Result	Timoshenko	de Winter	Shell	Langner	Tamano	Lohmeier	Nishioka	Small
1	17.5	1.36	11	8.2	13.0	14.6	17.0	< 0 (!)	15.9	7.4	17.0
2	21.1	0.10	23	21.6	26.9	25.9	29.4	24.9	29.8	20.2	29.8
3	21.1	0.40	14	12.5	18.1	20.5	23.4	15.5	21.8	12.0	22.0
4	21.1	1.43	10	5.6	8.7	10.0	13.7	< 0 (!)	11.4	5.0	12.3
5	28.9	0.87	6	4.2	6.2	7.8	12.7	2.6	9.3	3.7	9.7

6	28.9	0.35	9	7.2	9.8	11.8	17.7	9.0	14.8	7.9	15.0
7	37.3	0.21	6	5.1	6.3	7.3	14.6	5.5	12.7	4.9	12.8
8	37.3	0.10	7	6.3	7.3	7.7	16.3	6.7	15.4	8.5	15.4
9	40.4	1.54	2	1.4	2.0	2.6	6.8	< 0 (!)	3.5	1.2	3.8

Table 5 - Test Results for X 56 Steel Pipe Specimens with Initial Ovality

No.	D / t ratio	Initial Ovality (%)	Collapse Pressure Value (MPa)								
			Test Result	Timoshenko	de Winter	Shell	Langner	Tamano	Lohmeier	Nishioka	Small
1	35.4	1.20	3.8	2.3	3.3	16.1	46.0	0.2	5.5	2.8	5.6
2	35.4	0.70	5.0	3.3	4.5	17.9	35.5	3.4	7.9	4.4	8.0
3	27.1	0.70	9.0	5.7	8.4	21.9	46.5	6.2	12.2	7.1	12.3
4	22.0	0.80	13.0	7.9	12.0	25.3	60.4	7.4	15.5	9.2	15.8
5	22.0	0.40	17.0	11.9	17.0	29.1	47.0	16.2	21.2	14.5	21.5
6	18.7	0.90	17.8	10.0	15.5	28.9	75.2	7.4	18.8	11.2	19.2
7	18.7	0.50	22.0	14.3	21.2	33.0	59.4	18.1	24.5	16.5	24.9
8	16.3	1.50	17.5	9.0	14.4	28.6	113.4	< 0 (!)	17.5	9.7	17.9
9	16.3	1.30	19.0	10.0	16.0	30.0	104.4	< 0 (!)	19.0	10.9	19.5

Table 6 - Test Results for X 70 Steel Pipe (Coiled Tubing) Specimens with Initial Ovality

No	D / t	Initial	Collapse Pressure Value (MPa)

.	ratio	Ovality (%)	Test Result	Timoshenko	de Winter	Shell	Langner	Tamano	Lohmeier	Nishioka	Small	TF
1	15.2	0.50	22.0	26.2	38.1	54.4	95.3	30.2	42.4	29.7	43.1	22.5
2	15.2	0.90	16.0	18.7	38.1	48.4	120.8	12.5	33.5	20.8	34.3	16.9
3	15.2	1.20	14.0	15.5	24.3	44.7	139.8	1.31	28.9	17.0	29.7	14.4
4	12.8	0.50	30.0	35.2	50.4	65.4	113.2	38.5	53.2	38.5	54.1	30.0
5	12.8	0.70	26.0	29.6	44.2	61.9	128.3	26.9	47.6	32.2	48.6	26.1
6	12.8	1.10	20.0	22.5	35.2	55.8	158.5	6.4	39.3	24.3	40.4	20.8

All other formulas give results rather different with respect to the test data. For practical design, only the TF relationship can be recommended in this case as the other formulas always lead to critical pressure values greater than test results.

Finally, it can be concluded that, with the exception of coiled tubing, for which the TF equation (2.3) is the only one applicable for practical design, the most suitable equation to be used in the design process is the one proposed by de Winter (Table 1, pos. 2), imposed also by the recent DnV [4] and BSI [3] Codes. If one wants to remain on the conservative side and to accept eventually higher costs, the classic Timoshenko equation (Table 1, pos. 1), recommended by all the older Codes for line pipe design, can always be used.

The post-collapse configuration of the pipe specimens, have been also analysed during the tests program by cutting each specimen in the collapsed area. Figure 1 shows some of these specimens after testing and before sectioning. If considering the pipe transverse section, mainly two typical configurations have been identified, as follows:

- an ovalised pipe configuration reaching an “8”- shape (figure 2); such configuration corresponds to the theoretical one, especially in the case of plastic collapse and has been observed mainly for the specimens made of A and X70 steels;
- an oval pipe configuration, characteristic especially for collapse in the transition zone and observed mainly for the specimens made of X52 and X56 steels (figure 3); in some cases, when a surface defect (an initial imperfection) is present, the ovalised section tends towards to an “U”-shape configuration.

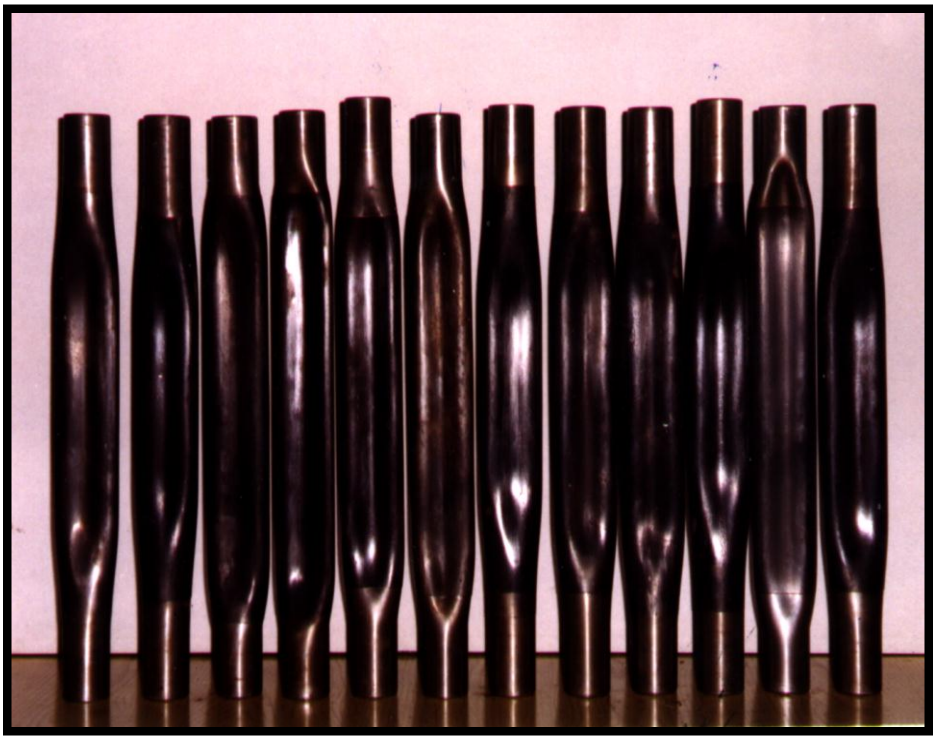

Figure 1 - Pipe Specimen after Testing and before Sectioning

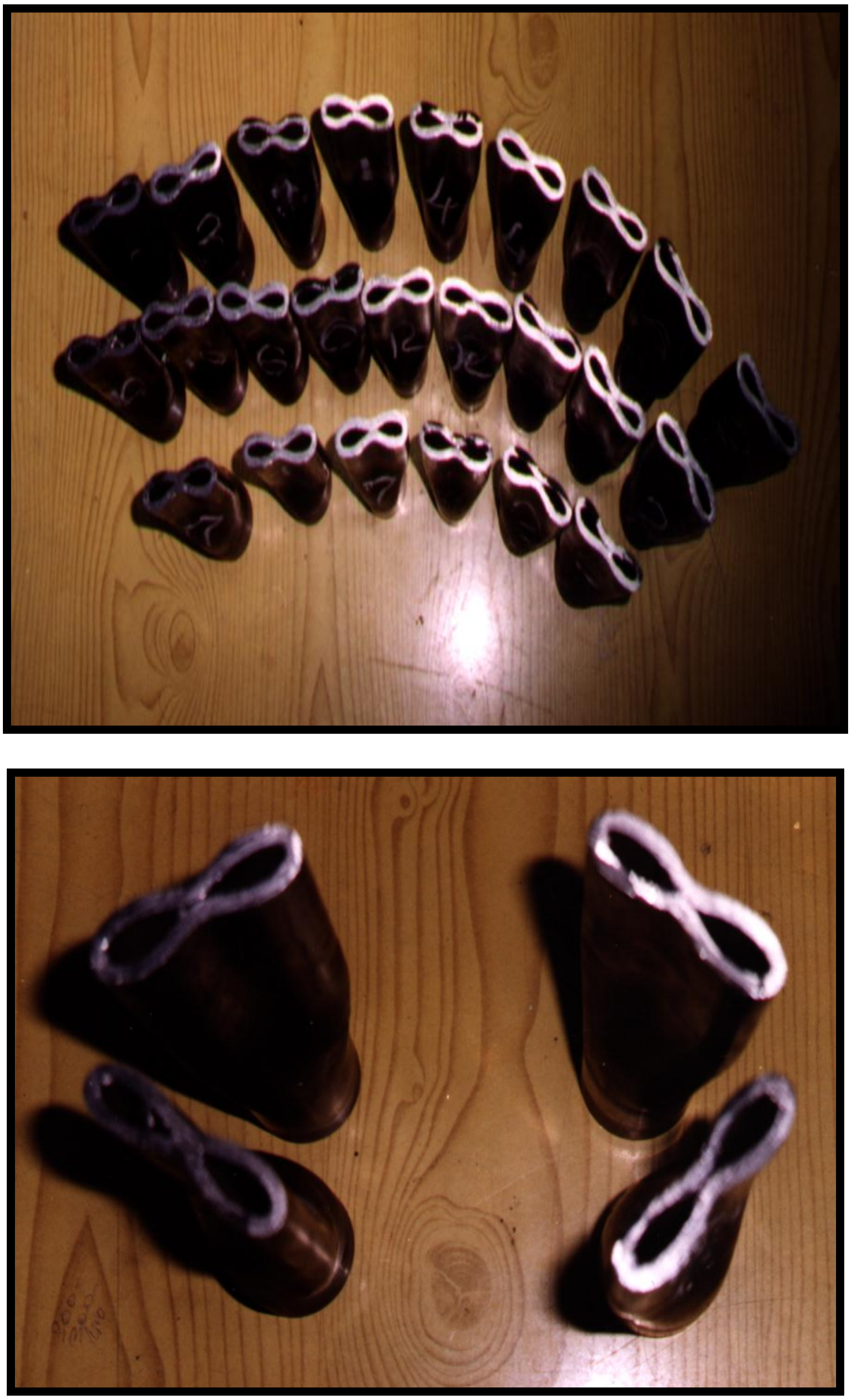

Figure 2 - Typical Post-buckling Configurations in Case of Plastic Collapse (A and X70 steel pipe specimens after sectioning)

Figure - 3 Typical Post- buckling Configurations in Case of Elastic-Plastic Collapse (X52 and X56 steel pipe specimens after sectioning)

4 CONCLUSIONS

> The tests performed, even if using a relatively small number of pipe specimens (31), allowed for an evaluation of the calculation methods proposed by various researchers in order to determine the influence of the pipe initial ovality on the critical external pressure at collapse for the case of oil industry tubulars.

> If comparing the relationships considered for the calculation of the critical collapse pressure for pipes with initial ovality with the test results, it can be concluded that the most adequate equation to be used in the design process is the one proposed by de Winter (Table 1, pos. 2), also recommended by the most recent DnV Code [4]. If a conservative evaluation is needed, the classic Timoshenko equation (Table 1, pos. 1) can always be used.

> The conclusion above is not valid for the case of coiled tubing, for which only the TF relationship (2.3) can be used for design, as all other formulas investigated predict collapse pressure values greater than test results.

> The experimental results described in this paper have been preceded by the investigation of the collapse phenomenon for the case of perfectly circular tubes (characterised by very small values of their geometrical imperfections). The results of these investigations have been included in a previous paper. All these results are the first step in a research activity aiming to define a calculation method for assessing the resistance capacity to local buckling of oil industry tubulars. Future test will be performed to study the influence of pipe material anisotropy, residual stress level, and also the effect of tensile/bending loads on the local buckling phenomenon.

ABSTRACT

An important load which can considerably affect the resistance capacity of oil industry tubulars (mainly casing and tubing in high pressure wells, and submarine pipelines installed in deep waters) is the external pressure, causing the pipe collapse phenomenon. Some of the factors with the greatest influence on pipe collapse behaviour are its geometrical imperfections (ovality, eccentricity, etc.).

This paper presents the results of research activities aimed to investigate the influence of the pipe initial ovality on the external pressure collapse phenomenon, in order to define design methodologies and criteria for assessing the external pressure resistance capacity of oil industry tubulars. To that purpose, some tests have been performed on small scale pipe specimens, based on the similitude law, and their results have been compared with the calculation formulas usually used to assess pipe collapse resistance capacity considering the influence of initial ovality.

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Поступила в редакцию 20 октября 2003 г.