ГОДИШНИК НА МИННО-ГЕОЛОЖКИЯ УНИВЕРСИТЕТ "СВ. ИВАН РИЛСКИ", Том 48, Св. I, Геология и геофизика, 2005
ANNUAL OF THE UNIVERSITY OF MINING AND GEOLOGY "ST. IVAN RILSKI", Vol. 48, Part I, Geology and Geophysics, 2005

RESEARCH CONCERNING THE LOCAL LOSS OF STABILITY UNDER EXTERNAL PRESSURE AND TENSION OF OIL INDUSTRY TUBULARS

Vlad Ulmanu, Dragos Gabriel Zisopol, Andrei Dumitrescu, Ciprian Nicolae Trifan

Petroleum-Gas University, Ploiesti 100680, Romania

ABSTRACT. Two of the most important loads which can decisively affect the resistance capacity of casing, tubing and submarine pipelines are the external pressure (causing the collapse phenomenon) and the tension, especially in high pressure wells and when installing deep water sea lines.
This paper presents the research activities based on the investigation of the external pressure (collapse) phenomenon, including the effect of the axial tension, for perfectly circular tubes in order to define the design methodologies and criteria for assessing the resistance capacity of oil industry tubulars.
For this purpose, the tests have been performed on small scale pipe specimens, based on the similitude law, and the results have been compared with the calculation formulae usually applied to assess the pipe resistance capacity to collapse with tension.

ИЗУЧАВАНЕ НА ЧАСТИЧНИТЕ ЗАГУБИ НА САТБИЛНОСТ ПРИ ВЪНШНО НАЛЯГАНЕ И НАПРЕЖЕНИЕ ПРИ ТРЪБИ ЗА ПЕТРОЛНАТА ИНДУСТРИЯ
Влад Улману, Драгос Габриел Зисопол, Андрей Думитреску, Циприан Николае Трифан
Университет за петрол и газ, Плоущ 100680р Румъния

Introduction

An important load 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 (loss of stability) phenomenon can occur leading to the ovalisation followed by flattening of tubulars. 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 present tendency of oil industry to move towards the exploitation of deeper and deeper oil wells and the installation of deep water submarine pipelines (the present world record water depth for such sealines is 2150 meters) led to increased requirements regarding the collapse resistance capacity of pipes for casing, tubing and sealines.
In such context, the research activities described in this paper aimed to investigate the local buckling phenomenon for perfectly circular tubes under the combined effect of external pressure and axial tension by performing some tests on small scale models, based on the similitude law. In the past, the authors have performed a series of experimental results to investigate the collapse phenomenon under external pressure only, including the effect of the pipe initial ovality (Dumitrescu, 1998; Zisopol, 2000; Dumitrescu and Zisopol, 2004; Zisopol and Dumitrescu, 2004).

In the future, the research will be continued by investigating the most important factors affecting the pipe local buckling phenomenon (geometrical imperfections of pipes for oil industry tubulars, mainly the initial pipe ovality; pipe material anisotropy, level of residual stress, etc.) and also the effect of bending loads on such phenomenon.

Review of previous results regarding local buckling of perfectly circular tubes

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, for perfectly circular (nominally round) pipes and to asses the influence of the axial tension, N, on such value.

The main problem emerging from these studies was that the local buckling mechanism differs essentially with the value of the ratio between the pipe outside diameter, D, and the pipe wall thickness, t. For great values of such ratio ($D/t > 35$), collapse (local buckling under external pressure only) occurs by means of an elastic flattening, before the pipe material reaches its yield strength. For small values of the D/t ratio (under 15...20), typical for instance for deep waters submarine pipelines, collapse will take place in the plastic field.

Finally, for D/t = 20...35, the pipe failure mechanism is much more complex – an elastic-plastic collapse will take place.

In case of elastic failure of a perfectly circular tube, the critical value of the external pressure (the so-called elastic collapse pressure) is given by the following equation (Langner, 1990):

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

where E is Young's elastic modulus of the tube material, and ν is Poisson's coefficient.

For tubes with thicker walls, for which a plastic collapse will occur, the critical external pressure value is dependant on the pipe material characteristics. Such value can be assessed either as the external pressure value for which the maximum circumferential stress reaches the yield strength or as the pressure value for which the entire transverse section of the tube plasticizes. If considering the thin-wall tubes theory, which assumes a constant value of the circumferential stress - σ_H - across the tube wall thickness, both variants above lead to the same value of the critical pressure (the so-called plastic collapse pressure):

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

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

In the transition zone between elastic and plastic collapse, characterised by comparable values of pressures p_E and p_F (for D/t = 15...35), a gradual passage is actually taking place from the elastic failure mechanism to the plastic one. As a consequence, the simplest calculation method for the critical pressure in such case is to assess the value of p_c as the minimum between the values of p_E and p_F. However, such assessment leads to collapse pressure values greater than the ones obtained as test results. Due to this reason, different calculation relationships have been proposed for a perfect circular tube, presented by Langner (1990) and Dumitrescu (1998). After investigating these relationships and comparing them with our experimental results (Dumitrescu, 1998; Zisopol and Dumitrescu, 2004), we have reached the conclusion that the best results are obtained using the following Shell relationship, proposed in 1975:

$$p_c = p_E \, p_F \, (p_E^2 + p_F^2)^{-1/2} \ . \qquad (3)$$

Equation (4) above has been developed for the case of a perfect circular tube (no geometrical imperfections, material anisotropy, etc. have been considered). That is not the case in practice, as a pipe is always affected by such imperfections and especially by ovalisation. The equations developed to include the effect of initial ovality of a tube on the critical collapse pressure values have been investigated in our previous work (Dumitrescu, 1998; Zisopol, 2000; Dumitrescu and Zisopol, 2004).

Our conclusion has been that the relationship proposed in 1981 by de Winter, imposed by the most recent internationally recognized Code dedicated to submarine pipelines (DnV, 2000; BSI, 1993), much used worldwide, leads to the best results:

$$(p_c - p_E)\,(p_c^2 - p_F^2) = p_c \, p_E \, p_F \cdot \delta_0 D/t \ , \qquad (4)$$

where δ_0 is the initial ovality of the pipe with a minimum recommended value of 0.5%.

In this paper, both equation (3) and (4) – with δ_0 = 0.5% - have been used to asses the value of p_c.

If, in addition to the external pressure, a tensile load is applied to the pipe, its resistance to local buckling decreases significantly.

Such reduction is governed by the ratio between the axial tensile stress, σ_L, and σ_c. This ratio is actually equal to the ratio between the axial tension, N, applied to the pipe and the axial force corresponding to yielding of the entire pipe section, given by the following equation:

$$N_F = \pi \, (D - t) \, t \, \sigma_c \ . \qquad (5)$$

Various researchers tried to account for the axial tension influence on the critical collapse pressure, p_c. The most recommended and used method (especially for submarine pipelines) is based on the von Mises combined stress theory and consists of adjusting the predicted collapse pressure value for axial tension (Dumitrescu, 1998). According to this method, the yield strength value, σ_c, is adjusted by multiplying it with the following correction coefficient:

$$\alpha_c = -\frac{1}{2} \cdot \frac{\sigma_L}{\sigma_c} + \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_L}{\sigma_c}\right)^2} \ , \qquad (6)$$

where the σ_L/σ_c ratio can be replaced with N/N_F.

The adjusted value of σ_c will be used to calculate the plastic collapse pressure using equation (2), and then the critical collapse pressure, using equations (3) or (4). This last value can be compared with the one calculated in the absence of the axial tension.

Another method to account for the axial tension effect is to use an interaction formula including the ratio between the critical pressure when the axial load is present, p_c, and the critical collapse pressure in the absence of the axial load, p_c^0, and the N/N_F ratio. After investigating several such formulas, Zisopol (2000) reached the conclusions that the best results are obtained for casing and tubing if using the following equation (developed initially for coiled tubing):

$$\left(\frac{p_c}{p_c^0}\right)^{\frac{4}{3}} + \left(\frac{N}{N_F}\right)^{\frac{4}{3}} = 1 \ , \qquad (7)$$

As it can be easily observed, 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 the pipe collapse phenomenon. As a consequence, tests can be performed on small diameter pipe specimens who can be considered small scale models of large diameter pipes.

Based on the statement above, a pipe local buckling testing facility (under external pressure and axial tension) has been designed and constructed. An image of the testing facility is shown in figure 2, while its scheme is included in figure 3.

The pressure chamber is shown in figure 1.

Fig. 1. Pressure chamber of the testing facility

The testing device can develop a maximum hydrostatic pressure of 1000 bar and a maximum axial tension of 100 kN, while the outside diameter of the pipe specimens can be 60 mm or, in case the lids (see fig. 3) are changed, 32 mm. The minimum required length of the pipe specimens is 500 mm.

Fig. 2. Local buckling testing facility

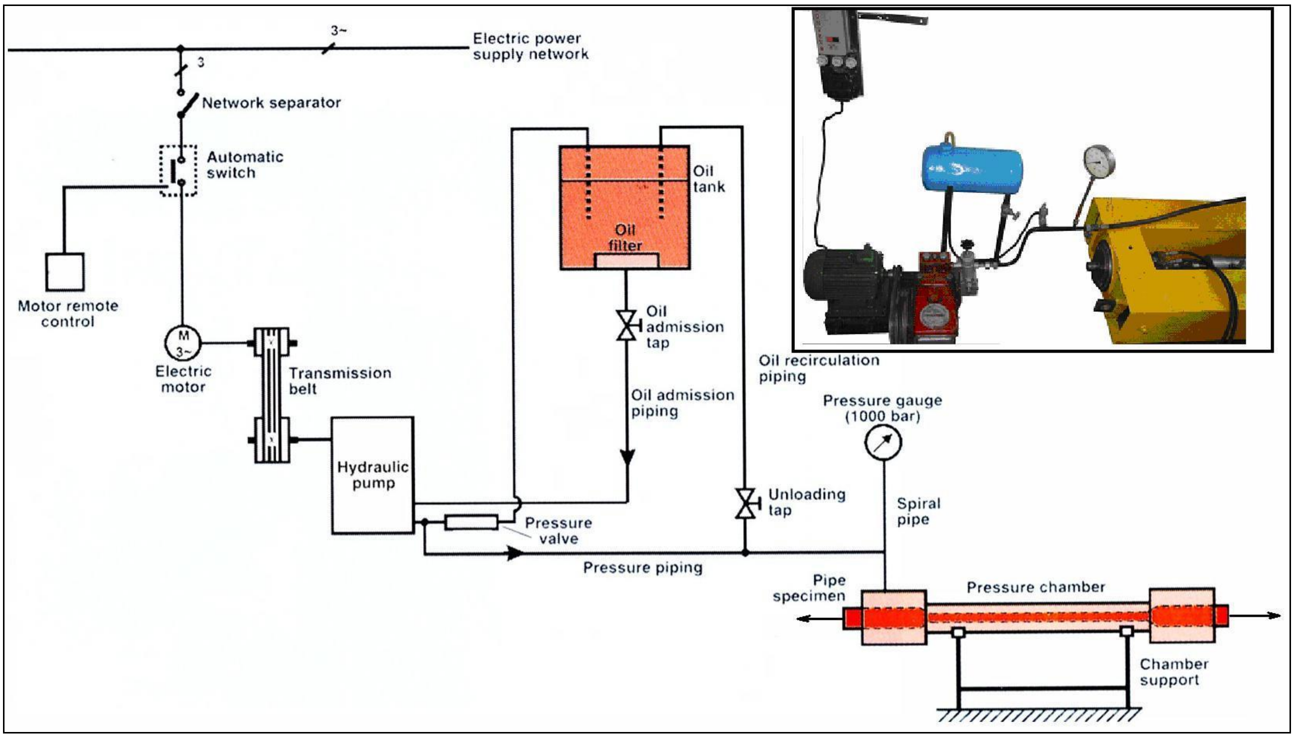

Fig. 3. Local buckling testing facility scheme

Experimental results regarding local buckling of perfectly circular pipes

The tests performed aimed at studying the local buckling phenomenon under external pressure and axial tension for tubes that can be considered perfectly circular (characterised by very low values of geometrical imperfections).

The tests have been performed using 24 steel specimens, which were taken from 6 seamless pipes (4 specimens from each pipe). The main characteristics of these pipes are shown in Table 1. The yield strength and the ultimate tensile strength values of the specimens' materials have been verified in each case by performing tensile tests on pipe samples, according to API methodology (API, 1980).

Table 1
Specimens Characteristics

No.	D/t Ratio	Material	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]
1	28	E235 EN10297/1	329	451
2	19.33			
3	12.4			
4	27.6	10MoCr10 STAS 3478	482	552
5	19.06			
6	12.24			

The pipe specimens have been machined both outside and inside in order to obtain very small values (under 0.1 %) of the initial pipe ovality. Moreover, the pipe eccentricity values, measured by cutting the specimens after testing, have been found to be sufficiently low (under 0.2 %) in order not to have any practical influence on the critical collapse pressure obtained during testing. Based on the above, it has been concluded that the 18 pipe specimens used for testing can be considered as perfectly circular tubes.

For each pipe tested, one specimen has been used to determine the critical collapse pressure in the absence of the axial force (N=0), while the other 3 have been firstly tensioned to an axial tension corresponding respectively to 40%, 70%, and 100% of N_F, given by equation (5).

The experimental values of p_c (obtained for N=0) have been compared with the results obtained using equations (3) or (4), combined with equations (1) and (2). A good agreement has been observed between experimental and theoretical results.

The experimental values of p_c in the presence of an axial tension have been compared with the results obtained using equation (7) or equation (6), combined with equation (2) and with equation (3) or (4). The three variants of theoretical results have been plotted as a dependence $p_c/p_c^0 = f(N/N_F)$.

The curves obtained, together with the test results are synthesised in figures 4-9 for each pipe used to obtain the investigated specimens. Figures 10 and 11 show some of the test specimens after testing, while figures 12 and 13 show some of the test specimens sectioned in the collapsed zone.

If comparing experimental test results with calculated values, a good agreement has been observed, with the exception of the tests for which N=N_F, due to the random factors affecting the pipe local buckling behaviour which cannot be included in the theoretical models.

The three calculation methods used to asses the critical collapse pressure in the presence of an axial tension have given very close results with the exception of pipes with *D*/*t* ratios close to 30. In these cases, the calculation methods based on equation (6), developed especially for the submarine pipelines, are recommended as such *D*/*t* ratios are typical for these pipelines.

The post-collapse configuration of a perfectly circular tube, i.e. with negligible geometrical imperfections, have been also analysed during the tests program.

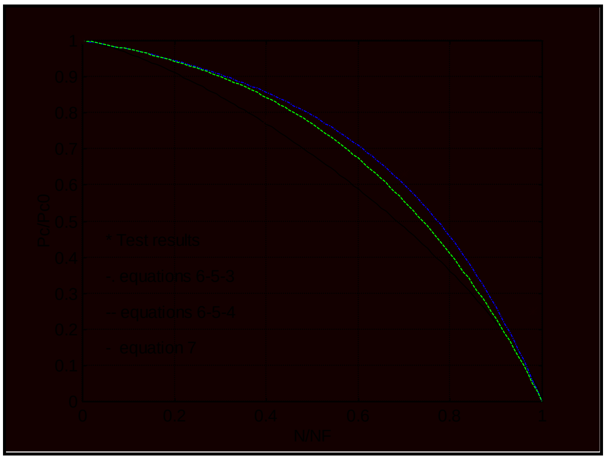

Fig. 4. Results for E235 steel, D/t=28

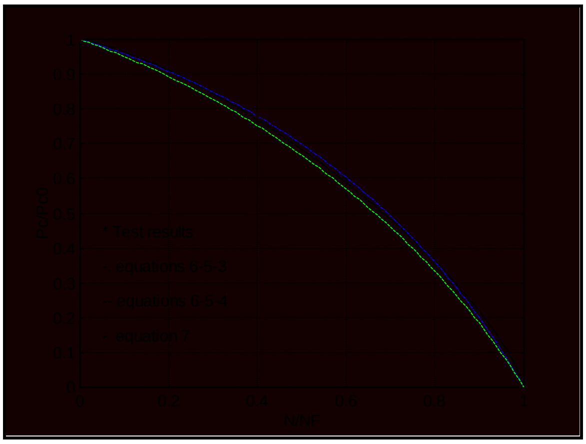

Fig. 5. Results for E235 steel, D/t=19.33

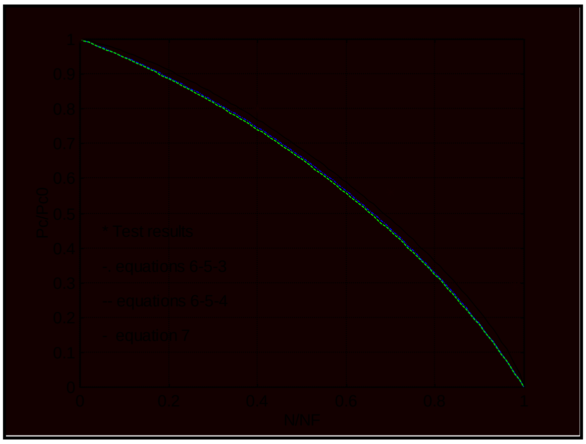

Fig. 6. Results for E235 steel, D/t=12.4

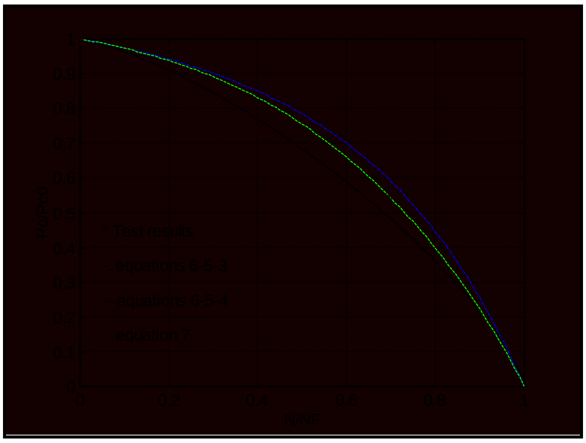

Fig. 7. Results for 10MoCr10 steel, D/t=27.6

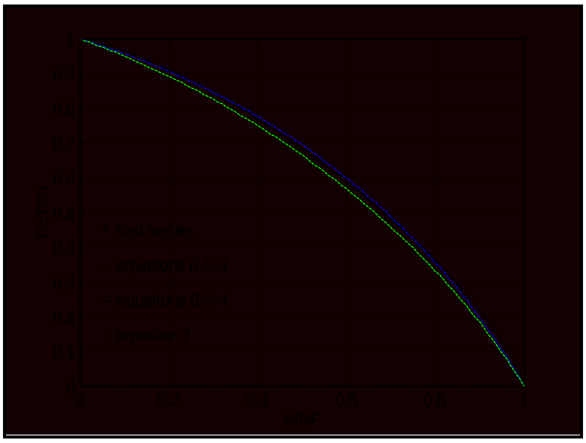

Fig. 8. Results for 10MoCr10 steel, D/t=19.06

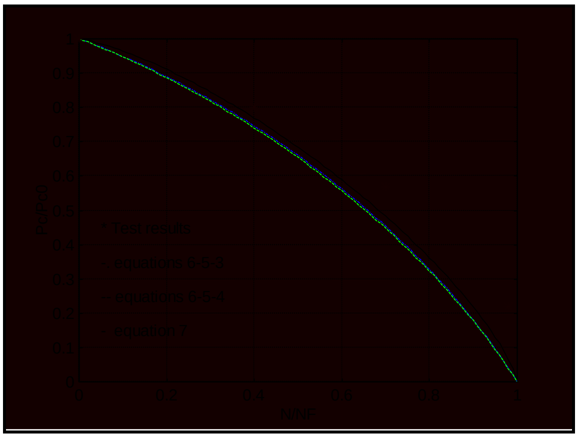

Fig. 9. Results for 10MoCr10 steel, D/t=12.24

Fig. 10. Collapsed test specimens made of E235 steel

Fig. 11. Collapsed test specimens made of 10MoCr10 steel

Fig. 12. Sectioned test specimens made of E235 steel

Fig. 13. Sectioned test specimens made of 10MoCr10 steel

If considering the pipe transverse section, two typical configurations have been identified, as follows (see figs. 12 and 13):

- an ovalised pipe configuration, with the pipe ovality increasing with the *D/t* ratio value, finally reaching an "8"-shape; such configuration corresponds to the theoretical one, especially in the case of plastic collapse;
- a total flattening of the pipe specimen, characteristic for an elastic collapse.

Conclusions

The tests performed, even if using a relatively small number of pipe specimens (24), allowed for an evaluation of the calculation methods proposed by various researchers in order to characterise the local buckling phenomenon under external pressure and axial tension for the case of perfectly circular tubes (characterised by small values, well below the allowed ones, of their geometrical imperfections).

If comparing the calculation methods considered to asses the influence of the axial tension on the critical collapse pressure for pipes without geometrical imperfections with the test results, it can be concluded that these three methods can be used in the same measure to evaluate such influence. The only exception has been observed for pipelines with *D/t* ratios close to 30, for which the calculation methods based on equation (6), developed especially for the submarine pipelines, are recommended.

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