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Experimental Results for Local Buckling under External Pressure (Collapse) and Axial Tension of Perfectly Circular Tubes

Vlad Ulmanu, Dragoş Gabriel Zisopol, Ciprian Nicolae Trifan

Universitatea Petrol – Gaze din Ploieşti, Bd. Bucureşti nr. 39, Ploieşti
e-mail: vulmanu@upg-ploiesti.ro

Abstract

The paper presents the results of an experimental study aimed to investigate the behaviour of perfectly circular tubes loaded by external pressure (collapse) and axial tension. The tests have been performed on small scale pipe specimens, based on the similitude law, and their results have been compared with collapse pressure values calculated with formulas usually used to assess pipe collapse under external pressure with axial tension.

Key words: *pipe, collapse, external pressure, axial tension.*

Introduction

An important loading which can decisively affect the resistance capacity of oil industry tubulars is the external hydrostatic pressure. Under the external pressure, often combined with tensile and/or bending loads, the local buckling 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 paper presents the experimental facility and the methodology applied in order to study the influence of the axial load on external collapse pressure for perfectly circular tubes by performing the tests on small scale models, based on the similitude law.

Analysis of previous results concerning collapse of ideal circular tubes

Various researchers proposed a series of calculation formulas, based on theoretical models and/or test results, to evaluate the critical external collapse pressure, p_c, for perfectly circular (nominally round) pipes. The main problem emerging from those studies is that the collapse mechanism differs essentially with the value of the ratio between the pipe outside diameter and its wall thickness, D/t [8].

For great values of D/t ratio ($D/t > 35$), collapse occurs by means of an elastic flattening, before the pipe material reaches its yield strength. However, for small values of the D/t ratio (under 15...20), typical for instance for deep water submarine pipelines, collapse will take place in the plastic field. As a consequence, in such case, an adequate modelling of the non-linear behaviour of pipe material becomes necessary. For D/t = 20...35, the pipe failure mechanism is much more complex – an elastic-plastic collapse will take place.

In case of elastic collapse of a perfectly circular tube, the critical value of the external pressure (the elastic collapse pressure) is given by the following equation:

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

where E is the Young's elastic modulus and ν is the 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 pipe 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 plastic collapse pressure):

$$p_c = p_F = 2R_{p0,2} \cdot t/D, \tag{2}$$

where $R_{p0,2}$ 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, from which the most important and also most used are the following:

- the formula proposed by Southwell (1914), which has been proven to be in most cases too conservative:

$$p_c = 1 / (1/p_E + 1/p_F); \tag{3}$$

- Shell relationship, proposed by Murphey and Langner (1975):

$$p_c = p_E\, p_F\, (p_E^2 + p_F^2)^{-1/2}\ ; \tag{4}$$

- the empirical formulation proposed by API [1] for casing, and obtained by processing a large amount of experimental data regarding casing failure.

The relationships shown above have 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.

This influence can be considered using the relationship proposed by de Winter (1981), imposed by the most recent internationally recognized Codes dedicated to submarine pipelines, i.e. "Det norske Veritas" OS-F101 [4], much used worldwide, and also by British Code BS 8010 [3]:

$$(p_c - p_E)\,(p_c^2 - p_F^2) = p_c p_E p_F \cdot \delta_0 D/t, \tag{5}$$

where δ_0 is the initial ovality of the pipe with a minimum recommended value of 0,5 % [4; 5].

In case when an axial tension and / or bending loads are added to the external pressure, the resistance capacity to local buckling will decrease meaningful. For the case of a combination between external pressure and axial tension, many theoretical and experimental studies have been performed, especially for casing pipes. Concerning the calculation relations applicable in the pipelines case, exists a lot of formulations, and one of these is based on the tangent coefficient of elasticity and rare used because it's hard to apply by experiment, and other one based on the von Mises equivalent stress criteria [6]. This variant, recommended by Fowler

(1990), proposes a correction of the yield strength $R_{p0,2}$, used in equation (*2*) for calculation of the critical value of the external pressure p_c, by multiplying it with the following coefficient [5]:

$$\alpha_c = -\frac{1}{2} \cdot \frac{\sigma_L}{R_{p0,2}} + \sqrt{1 - \frac{3}{4} \cdot \left(\frac{\sigma_L}{R_{p0,2}} \right)^2}\,, \tag{6}$$

where σ_L represents the axial load corresponding to the effective value of the axial tension applied to the tube. When the effective applied external pressure, p_C is relatively bigger in comparison to the loading level of the axial tension, the α_c coefficient is used directly for adjustment of the p_C / p_F ratio of the practical calculation relations. The calculation method based on the equation (*6*) was confirmed by experiments on thick wall tubes (D/t < 30).

In the case of a combined loading of coiled tubing subjected to external pressure (p_C) and axial tension (N), for determination of collapse pressure it is recommended the following equation [8]:

$$\left(\frac{p_C}{p_{CO}} \right)^{4/3} + \left(\frac{N}{N_F} \right)^{4/3} = 1\,, \tag{7}$$

where p_{CO} represents the yield pressure ($p_{CO} = 2 \cdot R_{p0,2} \frac{t}{D-t}$) and N_F is the yield tension ($N_F = \pi \cdot R_{p0,2} \cdot t \cdot (D-t)$).

The testing facility

In all above relations, 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 which can be considered small scale models of large diameter pipes [6]. Based on the above statement, a pipe collapse with axial tension testing facility has been designed and constructed [5; 8]. The scheme of the testing facility is shown in Figure 1, while its general view is presented in Figure 2. The design of the pressure chamber (see Fig. 1) is presented in Figure 3 and its general view is illustrated in Figure 4.

The testing device can develop a maximum hydrostatic pressure of 100 MPa, while the outside diameter of the pipe specimens can be 32 mm. The minimum required length of the pipe specimens is 650 mm. The pressure device is a hydraulic pump 2 PU 14, powered by an electric motor of 10 kW [8].

The testing facility also meets all requirements of API Code [1; 2], as follows:

- the pipe specimen must have a length at least two times greater than its nominal outside diameter;
- the specimen must be exposed at the test pressure along its entire length, while the testing device has to allow for any axial and/or radial deformations, and must not develop axial loads or internal pressure inside the specimen;
- the external surface of the specimen must be hydraulically loaded sufficiently slowly to allow for a precise reading of the collapse pressure value.

Experimental results concerning collapse with axial tension of perfectly circular pipes

The tests performed aimed at studying the collapse with axial tension phenomenon for tubes that can be considered perfectly circular (characterised by very low values of geometrical imperfections) [7]. The tests have been performed using 20 steel specimens (manufactured of

E235 steel and 10CrMo9-10 steel), which were taken from seamless pipes. The main characteristics of these specimens are shown in Table 1 [6].

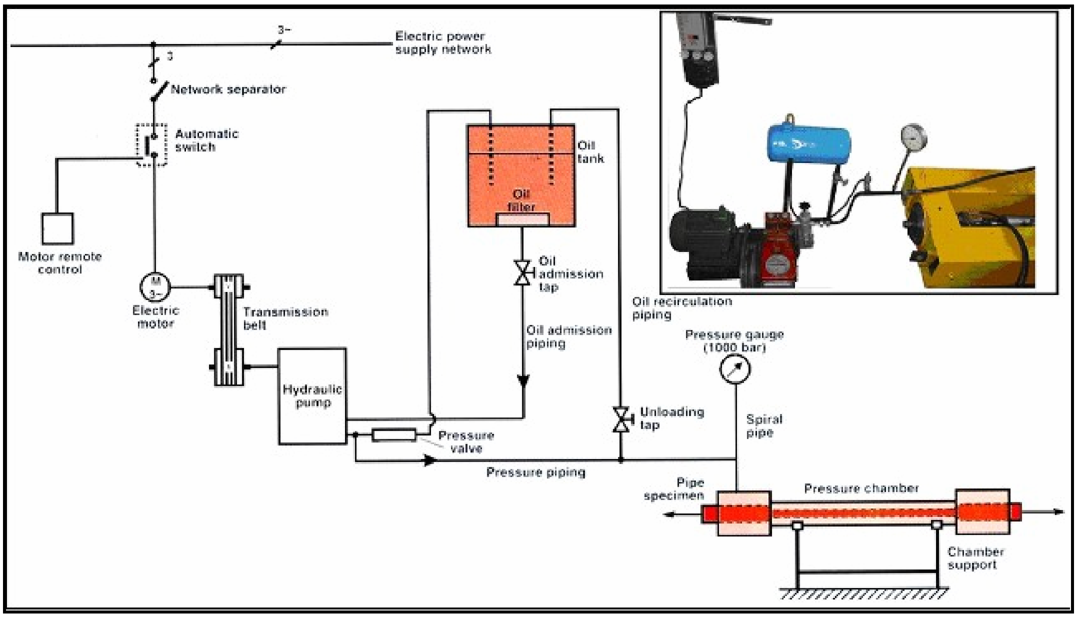

Fig. 1. The scheme of testing facility.

Fig. 2. The general view of the testing facility to external pressure (collapse) and axial tension.

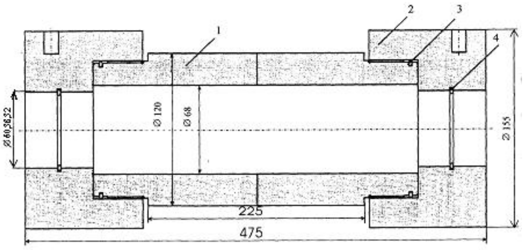

Fig. 3. The scheme of the pressure chamber
1 – body; 2 – lids; 3, 4 – sealing rings.

Fig. 4. The general view of the pressure chamber.

Table 1. Mechanical characteristics of the specimens.

Material	*Outside diameter*	*No. of samples*	*Yield Strength*	*Ultimate Tensile Strength*	*Chemical composition*	*Elongation*
	mm		*MPa*	*MPa*	*%*	*%*
E 235 EN 10297/1	28,7	5	322	437	C (0,117); Mn (0,544); P (0,007); S (0,006); Si (0,262); Al (0,020).	42,0
	27,0	5				
10CrMo9-10 EN 10025-2	28,7	5	320	662	C (0,130); Mn (0,610); P (0,009); S (0,006); Si (0,230); Al (0,025).	26,4
	26,4	5				

The outside diameter of the pipe specimens have been machined in order to obtain different values of the pipe wall thickness and therefore different values of the *D*/*t* ratio. In addition, very small values (under 0,1 %) of the initial ovality have also been obtained in such way. 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 presented values, it has been concluded that the 20 pipe specimens used for external pressure testing can be considered as perfectly circular tubes.

The experimental results are presented in Figure 5 for specimens made of E235 steel and in Figure 6 for specimens made of 10CrMo9-10 steel for a ratio D/t = 12,2 and in Figure 7 for specimens made of E235 steel and in Figure 8 for specimens made of 10CrMo9-10 steel, for a ratio D/t = 18,0 and 18,2 (*alfac.* represents the correction coefficient α_c – equation (*6*)).

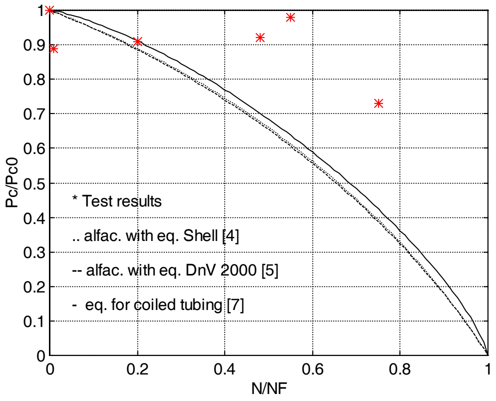

Fig. 5. Test results for E235 steel pipe specimens; D/t = 12,2

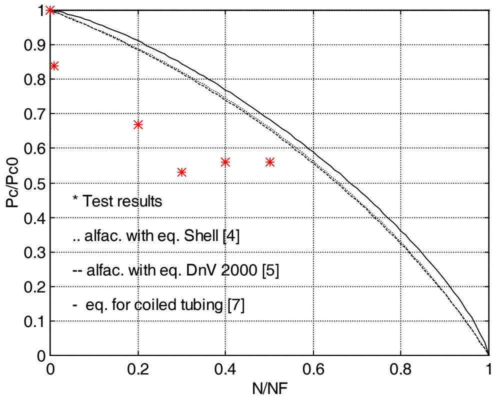

Fig. 6. Test results for 10CrMo9-10 steel pipe specimens; D/t = 12,2

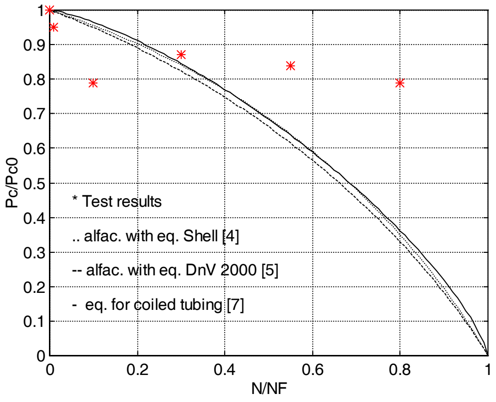

Fig. 7. Test results for E235 steel pipe specimens; D/t = 18,0

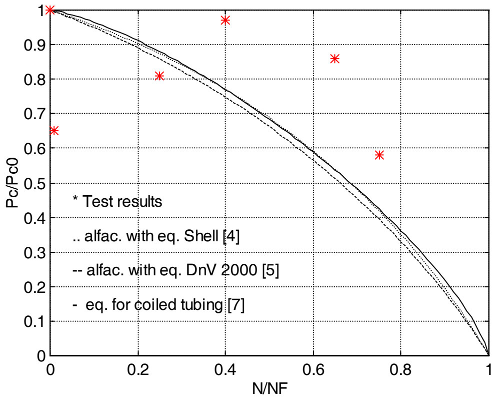

Fig. 8. Test results for 10CrMo9-10 steel pipe specimens, D/t = 18,2

As can be seen by comparing experimental test results with calculated values, the nearest collapse pressure values to the tests data are obtained using the equation (*7*) proposed for coiled tubing [8]. The only exception is the 10CrMo9-10 material specimens with D/t = 12,2 for which the closest values to test results are given by the DnV Code formula.

Conclusions

A testing facility was realised in order to study the collapse pressure of pipes under axial loading;

Comparing the relationships considered for the calculation of the critical collapse pressure with axial load for pipes without geometrical imperfections with the test results, it can be concluded that the most adequate equation to be used is that proposed for coiled tubing (*7*). The DnV Code [4] equation (*5*) leads to values very close to the ones given by Shell equation (*4*) and therefore both formulas can be used in the same measure to evaluate the critical pressure for pipes with negligible geometrical imperfections.

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Cercetări experimentale privind pierderea locală a stabilității tubingurilor perfect circulare sub influența presiunii exterioare (colaps) şi a forței axiale de tracțiune

Rezumat

Lucrarea prezintă rezultatele cercetării comportării țevilor petroliere perfect circulare la presiune exterioară (colaps) şi forță axială de tracțiune. Încercările experimentale au fost efectuate pe epruvete prelevate din tubing cu diametru mic, iar rezultatele au fost comparate cu cele obținute prin aplicarea formulelor de calcul utilizate uzual pentru evaluarea capacității de rezistență la colaps cu forță de tracțiune.