NEW METHOD FOR THE PREDICTION OF THE HYDROSTATIC COLLAPSE PRESSURE OF SUBMARINE PIPELINES

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Abstract. *In this paper the RCA V2 method, a new method for the prediction of the hydrostatic collapse pressure of submarine pipelines, is presented. Initially the basic characteristics of the problem are described and the equations of the following methods are presented: the DNV method, the RCA V1 method and the RCA V2 method. Then the RCA V2 database of nonlinear Finite Element (FE) analyses is described. This database contains the results of 110 nonlinear FE analyses. Finally the hydrostatic collapse pressures contained in the RCA V2 database are compared with those predicted by the already mentioned methods (the DNV method, the RCA V1 method and the RCA V2 method).*

Keywords: *Submarine pipelines, hydrostatic collapse pressure, nonlinear Finite Element analyses*

1 INTRODUCTION

The version 1 of the Renewed Classical Approach method (RCA V1 method) was published by Benjamin and Cunha in 2012 [1]. The development of this method, which is a modified version of the DNV method [2], was based on the hydrostatic collapse pressures contained in the RCA V1 database. The RCA V1 database contains a set of nonlinear Finite Element (FE) analyses of 13 infinitely long plain pipes. Each of the 13 pipes has an external diameter equal to 457 mm (18 in) and an external diameter to thickness ratio (D_e / t) which varies from 5 to 45. The only geometric imperfection considered is the ovalization of the pipe cross section, characterized by the ovality parameter f_o, which, for each pipe, has the following values: 0.005, 0.01, 0.02 and 0.04. As four FE analyses were carried out for each pipe, in total there are 52 FE analyses in the RCA V1 database.

The RCA method was originally developed to be a collapse checking method [1], i.e. a method composed of closed form equations used to perform the collapse check required by a pipeline design code. Afterwards this method was chosen to be the reference method of the version 1 of the BCA method [3].

The version 1 of the BCA method (BCA V1 method) was developed by Benjamin and Cunha [3] for the prediction of the hydrostatic collapse pressure of deepwater pipelines in service which contains a single corrosion defect. The corrosion defect geometry is described by the maximum defect depth d, the defect length L and the defect width w. The BCA V1 method adopts equations in which appears the collapse pressure of the pipe in two basic conditions: uncorroded pipe with external diameter D_e and wall thickness t and uniformly corroded pipe with external diameter D_{t*} and wall thickness $t*$. The wall thickness $t*$ is the minimum remaining wall thickness which is equal to the original wall thickness minus the maximum defect depth ($t* = t – d$). The external diameter D_{t*} of the uniformly corroded pipe is equal to D_e if the corrosion is internal and it is equal to $D_e – 2d$ if the corrosion is external. The collapse pressure $(p_{hc})_t$ of the uncorroded pipe and the collapse pressure $(p_{hc})_{t*}$ of the uniformly corroded pipe are calculated using the RCA V1 method.

The version 2 of the RCA method (RCA V2 method) was developed with the objective of extending the applicable range of the RCA method as follows: extend the applicable range of the method to encompass values of the ovality parameter f_o as small as 0.0025 and extend the applicable range of the method to encompass values of the external diameter to thickness ratio (D_e / t) as high as 300.

The first improvement was motivated by the trend in the design of deepwater pipelines toward requiring the tightest dimensional tolerances to maximize resistance to hydrostatic collapse [4,5]. For pipes manufactured by the UOE process the geometric characteristic to be improved is the out of roundness (ovality) of the pipe cross section which shall be as small as possible [4,5].

The second improvement is related to the RCA method in its role of reference method of the BCA method. It is not unlikely that the RCA method may have to calculate the collapse pressure of a uniformly corroded pipe whose D_{t*} / $t*$ ratio is greater than 45. An upper limit for the D_{t*} / $t*$ ratios that may occur is determined supposing that an internal corrosion defect with maximum depth equal to 90% of the wall thickness (d = 0.9 t) is found in a pipe whose D_e / t ratio is equal to 30. In this case the external diameter D_{t*} of the uniformly corroded pipe is equal to D_e and the minimum remaining wall thickness is equal to 10% of the wall thickness ($t*$ = 0.1 t) and therefore the D_{t*} / $t*$ ratio of the uniformly corroded pipe is equal to 300.

In this paper the RCA V2 method is presented. Initially the basic characteristics of the hydrostatic collapse of submarine pipelines are described and the equations of the following methods are presented: the DNV method [2], the RCA V1 method [1] and the RCA V2 method. Then an extended version of the RCA V1 database, named RCA V2 database, is described. Finally the hydrostatic collapse pressures contained in the RCA V2 database are compared with those predicted by the already mentioned methods (the DNV method, the RCA V1 method and the RCA V2 method).

2 BASIC CHARACTERISTICS OF THE HYDROSTATIC COLLAPSE OF SUBMARINE PIPELINES

As offshore oil and gas developments are steadily moving into deeper waters far from the coast [6], the number of large diameter export pipelines (diameters in excess of 16 in) installed in deep waters (water depths in excess of 1500 m) is increasing around the world [4,7].

The design of a submarine pipeline is carried out considering that during installation the pipeline is air-filled (empty). This assumption means that during installation the pipeline will have to withstand the external hydrostatic pressure of the sea.

As a pipeline is installed in deeper water, the external pressure that the pipe has to be able to withstand increases. Consequently the pipe becomes thicker.

For large diameter, heavy walled linepipe, the UOE pipe manufacturing process is the general method applied by pipe mills [8]. The name UOE stems from the initials of three mechanical steps which are carried out during the process (U for U-ing cold forming from the plate, O for O-ing cold forming from the Ushape and E for cold expansion to meet the geometric tolerances).

In ultra deep water projects (water depths in excess of 3000 m), where very thick walled UOE pipes are required, two issues among others have to be addressed [7]: there are few pipe mills that can manufacture the pipes (due to the small D_e / t ratio and to the tight dimensional tolerances) and there are few pipe laying vessels that can carry out the pipeline installation (due to the weight of the long suspended pipe string).

During installation the pipeline is empty and its portion that is resting on the seabed is subjected to an external overpressure (external pressure alone).

In service, if the transported fluid is gas, an external overpressure occurs when there is a shutdown of operation (scheduled or not). If the transported fluid is oil, an external overpressure occurs when after a shutdown of operation the line is evacuated (emptied).

From a structural point of view an empty pipeline resting on the seabed is a long tube subjected to an external hydrostatic pressure.

The literature on the failure behavior of long circular tubes subjected to external pressure is extensive. From the mid-19th century until the present day many documents on this subject (conference papers, original research articles, review articles, research project reports and book chapters) have been published. Besides the scientific interest the main motivations for these works were: the design of submarine pipelines, the design of pipe casings and in more recent times the design of steam generators tubes of nuclear power plants. For more details see two literature reviews which were published in 2012 (one focused on the classic methods [9] and the other a more comprehensive one [5]).

Depending on its external diameter to thickness ratio (D_e / t) the pipeline is classified as a thick tube (D_e / t less than 20) or as a thin tube (D_e / t equal to or greater than 20). Submarine pipelines usually have D_e / t ratios smaller than 30 while deepwater pipelines usually have D_e / t ratios smaller than 20. In this range of D_e / t ratios the failure behavior of an uncorroded pipeline subjected to an external pressure is characterized by the interaction between plasticity and geometric instability [8,9,10]. That is, yielding of the pipeline cross section begins before the collapse by geometric instability is attained.

Ideally the hydrostatic collapse pressure p_{hc} of a very thick tube is equal to the full yielding pressure p_{fy} while the collapse pressure p_{hc} of a very thin tube is equal to the elastic buckling pressure p_{eb}. In the intermediate range of D_e / t ratios plasticity and geometric nonlinearity interact and the hydrostatic collapse pressure is smaller than the smallest among the full yielding pressure p_{fy} and the elastic buckling pressure p_{eb}.

The failure behavior of an uncorroded pipeline subjected to an external pressure is governed by the geometric characteristics of the pipe cross section (the D_e / t ratio) and the pipe material properties (mainly the compressive yield strength) [8,9,10]. This failure behavior is also sensitive to initial imperfections introduced by the pipe manufacturing process, as for example: out-of-roundness (ovality) of the pipe cross section and reduction of the pipe compressive yield strength in the hoop direction [8,9,10].

Due to the complexity of the problem, the Nonlinear Finite Element Method is the best method to calculate the collapse pressure of a tube subjected to an external hydrostatic pressure. However a method composed of closed form equations, the so-called collapse checking method, is more adequate to perform the collapse check required by a design code.

The classic methods for the check of the hydrostatic collapse of long circular tubes are composed of the following closed form equations [9]:

- An equation for the prediction of the full yielding pressure p_{fy} of perfect circular tubes, relevant for very thick tubes;
- An equation for the prediction of the elastic buckling pressure p_{eb} of perfect circular tubes, relevant for very thin tubes;
- An equation for the prediction of the hydrostatic collapse pressure p_{hc} of nominal circular tubes, which in the limit of thick-walled tubes converges to the full yielding pressure p_{fy} of perfect circular tubes and in the limit of thin-walled tubes converges to the elastic buckling pressure p_{eb} of perfect circular tubes.

Besides the features listed above, a classic collapse checking method may also incorporate empirical factors to take into account the effect of imperfections introduced by the tube manufacturing process.

The DNV design code (DNV OS-F101 "Submarine Pipeline Systems" [2]) recommends a classic collapse checking method, called herein DNV method.

The DNV method is world wide accepted and to a certain extent is considered the industry standard in offshore pipeline engineering. This method, which is adequately accurate for D_e / t ratios in the range of 20 to 45, becomes increasingly conservative for D_e / t ratios smaller than 20 [1].

3 DNV METHOD

The equation used by the DNV method to calculate the hydrostatic collapse pressure p_{hc} of the pipeline is as follows [2]:

$$(p_{hc} - p_{eb})\ (p_{hc}^2 - p_{fy}^2) = p_{hc}\ p_{eb}\ p_{fy}\ f_o\ \frac{D_e}{t} \tag{1}$$

where,

$$p_{fy} = \sigma_{yield} \frac{2t}{D_e} \tag{2}$$

$$p_{eb} = \frac{2E}{(1-\nu)} \left(\frac{t}{D_e}\right)^3 \tag{3}$$

$$\sigma_{yield} = \alpha_{fab}\, \alpha_U\, \text{SMYS} \tag{4}$$

$$(f_o)_{calc} = \frac{(D_e)_{\max} - (D_e)_{\min}}{D_e} \tag{5a}$$

$$f_o = (f_o)_{calc} \tag{5b}$$

$$f_o = 0.005 \qquad \text{if} \quad (f_o)_{calc} < 0.005 \tag{5c}$$

E – Young's modulus of the pipe material

ν – Poisson's ratio of the pipe material

σ_{yield} – yield stress of the pipe material

α_{fab} – fabrication factor

α_U – material strength factor

SMYS – specified minimum yield stress of the pipe material

$(D_e)_{max}$ – maximum value of the pipe external diameter

$(D_e)_{min}$ – minimum value of the pipe external diameter

D_e – nominal external diameter of the pipe ($D_e = (1/2)\,(\,(D_e)_{max} + (D_e)_{min})\,$)

The fabrication factor α_{fab} (see Equation (4)) is used to take into account the effect of the pipe manufacturing process in the compressive yield stress in the hoop direction [2]. Table 1 present the values of the fabrication factor established in DNV OS-F101 [2]. The fabrication factor may be increased through heat treatment or external cold sizing (compression), if documented.

The material strength factor α_U (see Equation (4)) considers the different material qualification levels allowed in DNV OS-F101 [2]. The material strength factor depends on supplementary requirement U [2] as shown in Table 2.

Table 1 – Values of the fabrication factor α_{fab} established in DNV OS-F101

manufacturing process	seamless	UO&TRB&ERW	UOE
α_{fab}	1.00	0.93	0.85

Table 2 – Values of the material strength factor α_U established in DNV OS-F101

material qualification level	normally	supplementary requirement U
α_U	0.96	1.00

The lower bound of the value of the ovality parameter f_o established by Equation (5c) is a conservative precaution instead of an actual limitation of the method. For this reason all the collapse pressures $(p_{hc})_{DNV}$ predicted by the DNV method which will be presented in sections 7 and 8 were calculated using one of the five values of the ovality parameter f_o contained in the RCA V2 database, including the smaller one, i.e., f_o equal to 0.0025.

4 RCA V1 METHOD

The equation used by the RCA V1 method to calculate the hydrostatic collapse pressure p_{hc} of the pipeline is as follows [1]:

$$(p_{hc} - p_{eb})\,(p_{hc}^2 - p_{fy}^2) = p_{hc}\;p_{eb}\;p_{fy}\;f_K\;f_o\,\frac{D_m}{t} \qquad \text{for} \qquad f_o \le 0.04 \;\text{ and }\; \frac{D_e}{t} \ge 5 \tag{6}$$

where,

$$p_{fy} = \sigma_{yield}\,\frac{2t}{D_m} \tag{7}$$

$$p_{eb} = \frac{2E}{(1-\nu)}\left(\frac{t}{D_m}\right)^3 \tag{8}$$

$$D_m = D_e - t \tag{9}$$

$$\sigma_{yield} = \alpha_{fab}\,\alpha_U\,\text{SMYS} \tag{10}$$

$$(f_o)_{calc} = \frac{(D_e)_{\max} - (D_e)_{\min}}{D_e} \tag{11a}$$

$$f_o = (f_o)_{calc} \tag{11b}$$

$$f_o = 0.005 \qquad\qquad \text{if} \quad (f_o)_{calc} < 0.005 \tag{11c}$$

$$f_K = (f_I)_{0.5\%}\,(f_K)_{0.5\%} + (f_I)_{4.0\%}\,(f_K)_{4.0\%} \tag{12}$$

$$(f_I)_{0.5\%} = 1.1429 - 28.571\,f_o \tag{13}$$

$$(f_I)_{4.0\%} = 28.571\,f_o - 0.1429 \tag{14}$$

$$K = 0.01\left(\frac{D_m}{t} - 4\right) \qquad \text{for} \quad \frac{D_m}{t} \ge 4 \tag{15}$$

$$(f_K)_{0.5\%} = (310\,K^2 - 600\,K^3 + 1750\,K^4)\;e^{-9.2K} \tag{16}$$

$$(f_K)_{4.0\%} = 1.28\,(1 - e^{-27K} - 0.12\,K) \tag{17}$$

D_m – mean diameter of the pipe ($D_m = D_e - t$)

Equation (10) differs from the one previously presented by Benjamin and Cunha [1] in that herein the fabrication factor α_{fab} and the material strength factor α_U were included. These parameters are identical to the fabrication factor and the material strength factor adopted by the DNV method (see section 3 above).

Traditionally the geometry of the cross section of a circular cylindrical shell is described by the wall thickness t and the mean diameter D_m instead of the wall thickness t and the external diameter D_e [11]. In order to be sure that the traditional option is the best one for the collapse check of pipelines, at the very beginning of the RCA method development a study was carried out [1] in which the full yielding pressures and the elastic buckling pressures of 13 pipes, whose D_e / t ratios varies from 5 to 45, were calculated using Equations (2) and (3) and using Equations (7) and (8) and were compared with the ones predicted by the solid Finite Element (FE) models. Assuming that the FE results are the most accurate, it was concluded that the best performance was achieved by Equations (7) and (8) because they predicted full yielding pressures and elastic buckling pressures closest to the ones predicted by the FE models [1].

The RCA V1 method is a modified version of the DNV method. The starting point for the development of the RCA V1 method was a modified version of the DNV method which differs from the original version of the DNV method in that the external diameter D_e was replaced by the mean diameter D_m in Equations (1), (2) and (3). Unfortunately the collapse pressures predicted by this first prototype of the RCA method were highly unconservative for D_e / t ratios greater than 15 when compared with the ones predicted by the solid FE models, irrespective of the value of the ovality parameter f_o considered.

In order to get a better agreement between the collapse pressures predicted by the RCA V1 method and the ones predicted by the FE models the empirical parameter f_K was introduced in Equation (6). The role of the parameter f_K is to decrease or increase the influence of the ovality on the collapse pressure. If f_K is smaller than the unity the influence of the ovality is decreased. If f_K is greater than the unity the influence of the ovality is increased. The parameter f_K is a function of other two parameters: the mean diameter to thickness ratio (D_m / t) and the ovality parameter f_o.

In the development of the RCA V1 method it was assumed that the relation between f_K and D_m / t is nonlinear and the relation between f_K and f_o is linear within the interval defined by two values of the ovality parameter f_o, namely: 0.005 and 0.040. Based on these assumptions two expressions of f_K in function of D_m / t (Equations (16) and (17)) were established by means of a trial-and-error process. For each of the Equations (16) and (17), several candidate expressions were tested until the pressures predicted by Equation (6) were considered close enough to the collapse pressures contained in the RCA V1 database. The values of f_K for the values of f_o greater than 0.005 and smaller than 0.04 must be determined by means of a linear interpolation (Equation (12)).

Figures 1 and 2 present the curves of the parameter f_K versus the D_e / t ratio, for the RCA V1 method, correspondent to four values of the ovality parameter f_o, namely: 0.005, 0.01, 0.02 and 0.04. The curves correspondent to f_o equal to 0.005 and f_o equal to 0.04 were determined using Equations (16) and (17), respectively, while the curves correspondent to f_o equal to 0.01 and f_o equal to 0.02 were determined using linear interpolation (Equation (12)).

Figure 1 presents the curves of f_K versus D_e / t for D_e / t values varying from 5 to 45. This was the range of variation originally assumed for the D_e / t ratio in the development of the RCA V1 method. In this range of D_e / t ratios the accuracy of the values of the parameter f_K, generated by Equations (12) to (17), has already been proved. In a previous study [1] the collapse pressures ($(p_{hc})_{FE}$) contained in the RCA V1 database of nonlinear Finite Element (FE) analyses were compared with those predicted by the DNV method ($(p_{hc})_{DNV}$) and the RCA V1 method ($(p_{hc})_{RCA\ V1}$). The best performance was achieved by the RCA V1 method that predicted collapse pressures closest to the ones predicted by the FE models.

Figure 2 presents the curves of f_K versus D_e / t for D_e / t values varying from 5 to 300. For D_e / t ratios greater than 45 the accuracy of the values of the parameter f_K, generated by Equations (12) to (17), has not been proved yet. Judging only by the values of the parameter f_K and the shape of the curves, the upper limit of the applicable range of Equations (12) to (17) should not be extended from 45 to 300. Except for the curve correspondent to f_o equal to 0.04, for D_e / t ratios greater than 45, a majority of the values of the parameter f_K are smaller than the unity. At first glance such small values of the parameter f_K could lead to the prediction of highly unconservative collapse pressures. In fact the performance of Equations (12) to (17) for D_e / t ratios greater than 45 is not so bad. As it will be shown in section 8, for this range of D_e / t ratios, among 45 collapse pressures predicted by the RCA V1 method, 28 collapse pressures (62.2%) are moderately unconservative ($(p_{hc})_{FE} < (p_{hc})_{RCA\ V1} \leq 1.05\ (p_{hc})_{FE}$) and only three (6.7%) are highly unconservative ($(p_{hc})_{RCA\ V1} > 1.05\ (p_{hc})_{FE}$). This amount of high unconservatism is relatively small and could be corrected by the use of an adequate safety factor when calculating the allowable external pressure. Even so it was deemed that a better approach would be to develop entirely new equations to calculate values of the parameter f_K which preclude the prediction of highly unconservative collapse pressures for pipes with D_e / t ratios greater than 45.

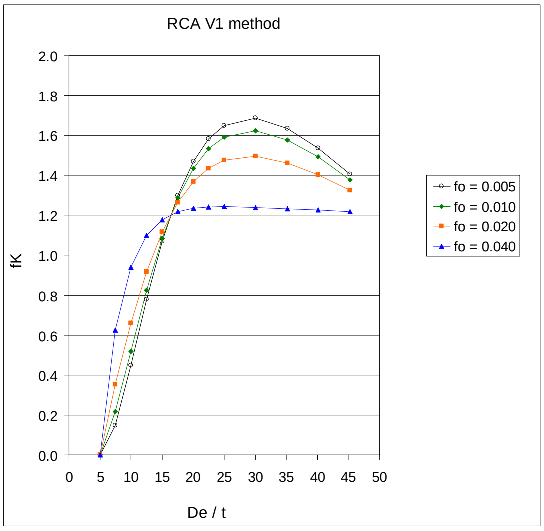

Figure 1 – Curves of f_K versus D_e / t for D_e / t values varying from 5 to 45 for the RCA V1 method

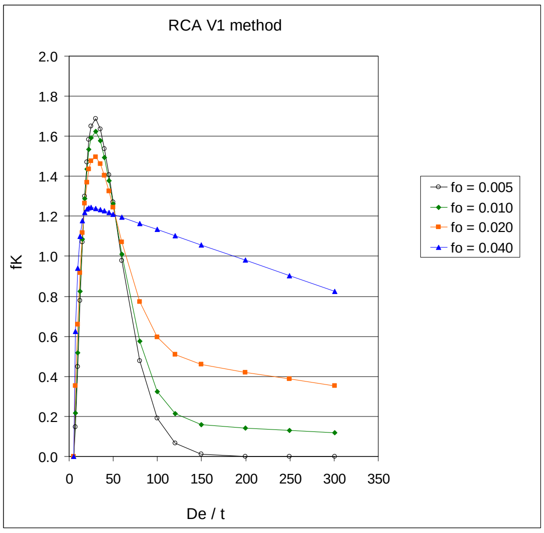

Figure 2 – Curves of f_K versus D_e / t for D_e / t values varying from 5 to 300 for the RCA V1 method

The lower bound of the value of the ovality parameter f_o established by Equation (11c) is an actual limitation of the method. For this reason all the collapse pressures $(p_{hc})_{RCA\ V1}$ predicted by the RCA V1 method which will be presented in sections 7 and 8 were calculated using one of the five values of the ovality parameter f_o contained in the RCA V2 database, except the smaller one, i.e., when f_o was equal to 0.0025 it was assumed that f_o was equal to 0.005.

5 RCA V2 METHOD

The main equations of the methods RCA V2 and RCA V1 are identical, i.e., the methods share Equations (6) to (10). Due to space limitations only the equations which are not the same are presented in this section.

In the RCA V2 method the ovality parameter f_o is calculated using Equations (18), presented below, instead of Equations (11) adopted by the RCA V1 method.

$$(f_o)_{calc} = \frac{(D_e)_{max} - (D_e)_{min}}{D_e} \tag{18a}$$

$$f_o = (f_o)_{calc} \tag{18b}$$

$$f_o = 0.0025 \qquad \text{if} \quad (f_o)_{calc} < 0.0025 \tag{18c}$$

In the RCA V2 method the parameter f_K is calculated using Equations (19) to (34), presented below, instead of Equations (12) to (17) adopted by the RCA V1 method.

$$f_K = (f_I)_{12}\,(f_K)_{0.25\%} + (f_I)_{21}\,(f_K)_{0.50\%} \qquad \text{for} \quad 0.0025 \le f_o \le 0.0050 \tag{19a}$$

$$f_K = (f_I)_{23}\,(f_K)_{0.50\%} + (f_I)_{32}\,(f_K)_{1.00\%} \qquad \text{for} \quad 0.0050 \le f_o \le 0.0100 \tag{19b}$$

$$f_K = (f_I)_{34}\,(f_K)_{1.00\%} + (f_I)_{43}\,(f_K)_{2.00\%} \qquad \text{for} \quad 0.0100 \le f_o \le 0.0200 \tag{19c}$$

$$f_K = (f_I)_{45}\,(f_K)_{2.00\%} + (f_I)_{54}\,(f_K)_{4.00\%} \qquad \text{for} \quad 0.0200 \le f_o \le 0.0400 \tag{19d}$$

$$r = 100\ f_o \tag{20}$$

$$(f_I)_{12} = 2 - 4\,r \qquad \text{for} \quad 0.0025 \le f_o \le 0.0050 \tag{21}$$

$$(f_I)_{21} = -1 + 4\,r \qquad \text{for} \quad 0.0025 \le f_o \le 0.0050 \tag{22}$$

$$(f_I)_{23} = 2 - 2\,r \qquad \text{for} \quad 0.0050 \le f_o \le 0.0100 \tag{23}$$

$$(f_I)_{32} = -1 + 2\,r \qquad \text{for} \quad 0.0050 \le f_o \le 0.0100 \tag{24}$$

$$(f_I)_{34} = 2 - r \qquad \text{for} \quad 0.0100 \le f_o \le 0.0200 \tag{25}$$

$$(f_I)_{43} = -1 + r \qquad \text{for} \quad 0.0100 \le f_o \le 0.0200 \tag{26}$$

$$(f_I)_{45} = 2 + 0.5\,r \qquad \text{for} \quad 0.0200 \le f_o \le 0.0400 \tag{27}$$

$$(f_I)_{54} = -1 + 0.5\,r \qquad \text{for} \quad 0.0200 \le f_o \le 0.0400 \tag{28}$$

$$s = \frac{1}{300}\left(\frac{D_m}{t} - 4\right) \qquad \text{for} \quad \frac{D_m}{t} \ge 4 \tag{29}$$

$$(f_K)_{0.25\%} = [(1+e^{-130s})^{-1} + 1000s^2 e^{-26.5s} - 1.6s + 15.9s^2 - 14.9s^3 + 6s^4]\,(1+10000e^{-210s})^{-1} \tag{30}$$

$$(f_K)_{0.5\%} = (1+200e^{-130s})^{-1} + 990s^2 e^{-26s} - 2.2s + 17s^2 - 16.1s^3 + 6.4s^4 \tag{31}$$

$$(f_K)_{1.0\%} = 0.7\,(1+194e^{-165s})^{-1} + 1000s^2 e^{-27s} + 1.9s + 1.8s^2 + s^3 \tag{32}$$

$$(f_K)_{2.0\%} = 1.5\,(1 - e^{-20s}) + 2000s^2 e^{-45s} - 2s + 5.5s^2 - 1.8s^3 + 0.6s^4 \quad (33)$$

$$(f_K)_{4.0\%} = 1.3\,(1 - e^{-81s}) - s + 3.4s^2 - 0.5s^3 \quad (34)$$

The RCA V2 method was developed with the objective of extending the applicable range of the RCA method as follows: extend the applicable range of the method to encompass values of the ovality parameter f_o as small as 0.0025 and extend the applicable range of the method to encompass values of the external diameter to thickness ratio (D_e / t) as high as 300. In order to achieve this objective it was decided to develop entirely new equations to substitute the equations which were used to calculate the values of the parameter f_K in the RCA V1 method.

In the development of the RCA V2 method it was assumed that the relation between f_K and D_m / t is nonlinear and the relation between f_K and f_o is piecewise linear within the subintervals defined by five values of the ovality parameter f_o, namely: 0.0025, 0.005, 0.010, 0.020 and 0.040. Based on these assumptions five expressions of f_K in function of D_m / t (Equations (30) to (34)) were established by means of a trial-and-error process. For each of the five equations (Equations (30) to (34)), several candidate expressions were tested until the pressures predicted by Equation (6) were considered close enough to the collapse pressures contained in the RCA V2 database. The values of f_K for the intermediate values of f_o must be determined by means of a piecewise linear interpolation (Equations (19a), (19b), (19c) and (19d)).

Figures 3 and 4 present the curves of the parameter f_K versus D_e / t, for the RCA V2 method, correspondent to five values of the ovality parameter f_o, namely: 0.0025, 0.005, 0.010, 0.020 and 0.040. These curves were determined using Equations (19) to (34). One obvious difference in relation to Figures 1 and 2 is that Figures 3 and 4 present five curves instead of four because, in the development of the RCA V2 method, besides the original four values of the ovality parameter f_o it was considered a fifth value (equal to 0.0025). The fifth curve corresponds to this new minimum value.

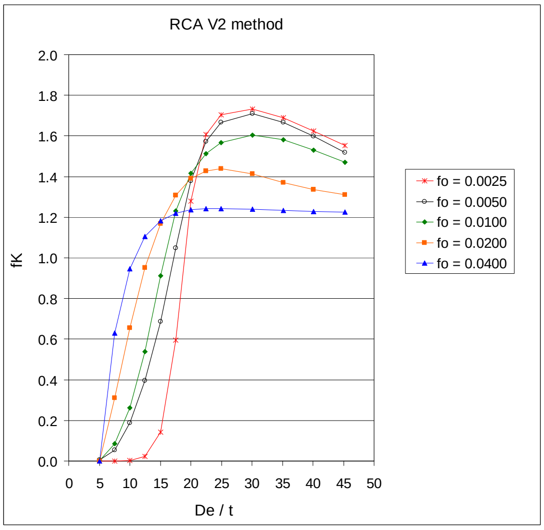

Figure 3 – Curves of f_K versus D_e / t for D_e / t values varying from 5 to 45 for the RCA V2 method

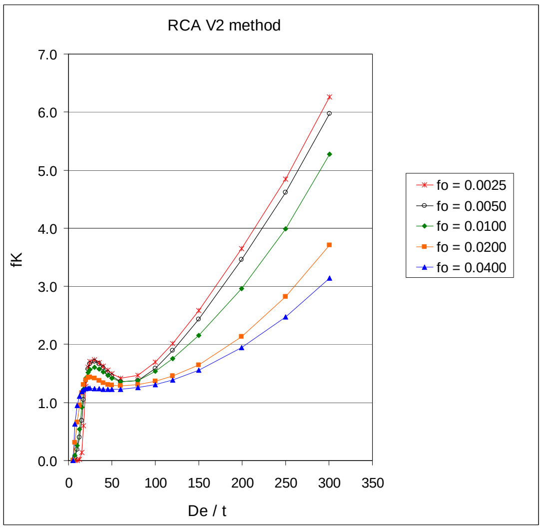

Figure 4 – Curves of f_K versus D_e / t for D_e / t values varying from 5 to 300 for the RCA V2 method

Figure 3 presents the curves of f_K versus D_e / t for D_e / t values varying from 5 to 45. This was the range of variation originally assumed for the D_e / t ratio in the development of the RCA V1 method. In this range of D_e / t ratios, the accuracy of the values of the parameter f_K, generated by Equations (19) to (34), will be proved ahead in section 7. Comparing each of the four curves presented in Figure 1 with its counterpart presented in Figure 3 it can be seen that a majority of the values (71%) of the parameters f_K generated by Equations (19) to (34) are equal to or smaller than the ones generated by Equations (12) to (17), i.e. they are less conservative.

Figure 4 presents the curves of f_K versus D_e / t for D_e / t values varying from 5 to 300. For D_e / t ratios greater than 45, the accuracy of the values of the parameter f_K, generated by Equations (19) to (34), will be proved ahead in section 8. In this range of D_e / t ratios the values of the parameter f_K generated by Equations (19) to (34) are greater than the unity with the objective of precluding the prediction of highly unconservative collapse pressures.

6 RCA V2 DATABASE OF NONLINEAR FE ANALYSES

The ANSYS program [12], a well known general-purpose Finite Element (FE) program, was employed to perform the nonlinear FE analyses of 22 infinitely long plain pipes. These pipes are made of an API 5L X65 steel (σ_{yield} = SMYS = 448 MPa) and were manufactured by the UOE process. It is assumed that during the pipe manufacturing process the heat treatment and the tests required (supplementary requirement U) by DNV OS-F101 [2] were carried out. Consequently for these pipes the fabrication factor α_{fab} and the material strength factor α_U can be considered equal to the unity ($\alpha_{fab} = 1$ and $\alpha_U = 1$).

Each of the 22 pipes has an external diameter equal to 457 mm (18 in) and an external diameter to thickness ratio (D_e / t) which varies from 5 to 300. The only geometric imperfection considered is the ovalization of the pipe cross section, characterized by the ovality parameter f_o, which, for each pipe, has the following values: 0.0025, 0.005, 0.010, 0.020 and 0.040. As five FE analyses were carried out for each pipe, in total there are 110 FE analyses in the RCA V2 database.

Two types of FE models were used: a solid model and a shell model.

The analyses of the 13 thickest pipes ($D_e / t \leq 45$) were carried out using solid FE models while the analyses of the 9 thinnest pipes ($D_e / t > 45$) were carried out using shell FE models. This approach was adopted because, for D_e / t ratios greater than 45, shell FE models are computationally more cost effective than solid FE models and achieve a level of accuracy similar to the level of accuracy that solid FE models achieve for D_e / t ratios smaller than 45.

The analyses accounted for stress stiffening and large displacements (geometric nonlinearity). It was assumed that the pipe material is an elastic perfectly plastic material whose stress-strain curve is presented in Figure 5. A rate-independent plasticity model using the von Mises yield criterion and isotropic hardening rule was adopted. A modulus of elasticity (E) of 200,000 MPa and a Poisson's ratio (ν) of 0.3 were used.

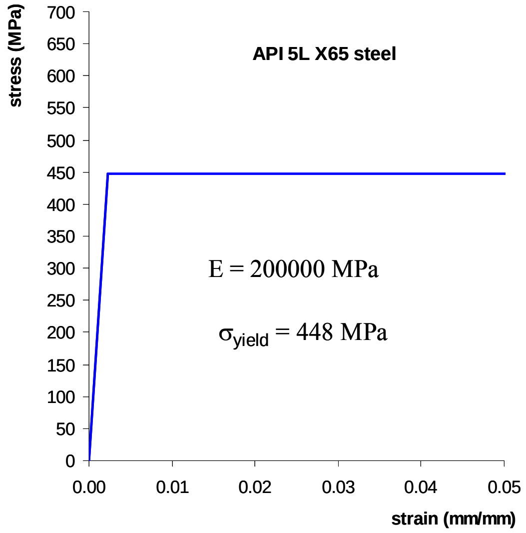

Figure 5 – Stress-strain curve used in the Finite Element analyses

The external pressure was applied in small increments and an arc length algorithm was used to guarantee that the analysis would go beyond the critical point of the equilibrium path.

The analyses were carried out with the objective of calculating the collapse pressure p_{hc} of the pipe. It was assumed that the collapse pressure p_{hc} is the maximum pressure applied to the pipe during the analysis.

Comparing the description of the RCA V2 database with the description of the RCA V1 database (see section 1) it is easy to see that, except for the pipes with ovality parameter f_o equal to 0.0025, all the analyses of the RCA V2 database which were carried out using solid FE models constitute what is being called herein the RCA V1 database. These analyses have been carried out as part of the development of the RCA V1 method [1].

The solid FE models were constructed using the PLANE42 element, available in ANSYS FE library, which is a four node plane strain element with two degrees of freedom at each node (2 translations). To take advantage of symmetry only one quarter of the pipe cross section was modeled. Appropriate boundary conditions were applied at the symmetry planes.

Table 3 presents the basic geometric and material data of the 13 thickest pipes ($D_e / t \leq 45$). These pipes were discretized by solid FE models. In the last column of Table 3 it is presented the number of elements through thickness (noel) used in these FE models. The dimension of the solid elements in the circumferential direction was established pursuing an aspect ratio approximately equal to the unity.

As an illustration, Figure 6 presents the solid FE mesh of the pipe LT15.0 without initial ovalization while Figure 7 presents the solid FE mesh of the pipe LT15.0 with an initial ovalization equal to 4% ($f_o = 0.04$). As an ovalization of 4% is too small to be perceived in a true scale plot the initial out-of-roundness was amplified in the plot shown in Figure 7.

Table 4 presents the collapse pressures of the 13 thickest pipes ($D_e / t \leq 45$) which were predicted by the solid FE models.

Table 3 – Basic geometric and material data of the 13 thickest pipe (D_e / $t \leq 45$)

Pipe	t (mm)	D_e / t	noel
LT05.0	91.4	5.0	32
LT07.5	60.9	7.5	24
LT10.0	45.7	10.0	16
LT12.5	36.5	12.5	16
LT15.0	30.4	15.0	16
LT17.5	26.1	17.5	16
LT20.0	22.8	20.0	8
LT22.5	20.3	22.5	8
LT25.0	18.3	25.0	8
LT30.0	15.2	30.1	8
LT35.0	13.0	35.2	8
LT40.0	11.4	40.1	4
LT45.0	10.1	45.2	4
D_e = 457 mm			
API 5L X65 steel			
SMYS = 448 MPa			
E = 200000 MPa			
ν = 0.3			

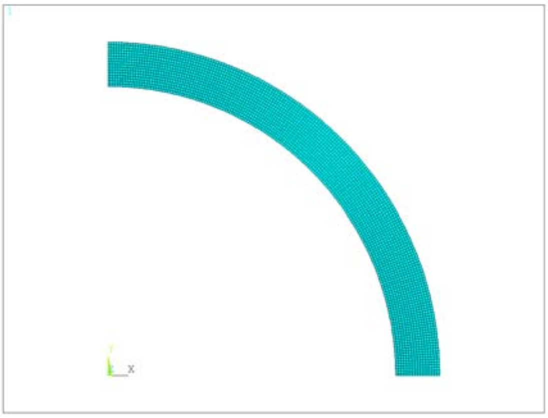

Figure 6 – Solid FE mesh of the pipe LT15.0 without ovalization

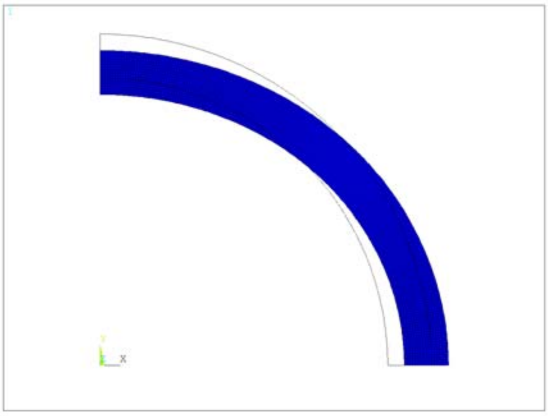

Figure 7 – Solid FE mesh of the pipe LT15.0 with initial ovalization equal to 4.0% (out of scale to be perceived)

Table 4 – Collapse pressures of the 13 thickest pipes predicted by the solid FE models

Pipe	$(p_{hc})_{\mathrm{FE}}$ (MPa)				
	$f_o = 0.0025$	$f_o = 0.0050$	$f_o = 0.01$	$f_o = 0.02$	$f_o = 0.04$
LT05.0	258.99	256.91	253.48	247.23	235.75
LT07.5	153.00	150.85	147.28	140.66	129.16
LT10.0	107.69	105.53	101.6	94.62	83.46
LT12.5	81.80	79.42	75.13	67.97	57.74
LT15.0	64.88	62.24	57.59	50.62	41.71
LT17.5	52.73	49.71	44.92	38.54	31.1
LT20.0	42.76	39.47	34.98	29.53	23.57
LT22.5	34.23	31.23	27.45	23.04	18.31
LT25.0	26.86	24.55	21.58	18.19	14.48
LT30.0	16.24	15.11	13.55	11.56	9.31
LT35.0	10.30	9.74	8.99	7.71	6.30
LT40.0	6.99	6.67	6.15	5.42	4.50
LT45.0	4.87	4.68	4.36	3.88	3.27

The shell FE models were constructed using the SHELL181 element, available in ANSYS FE library, which is a four node shell element with six degrees of freedom at each node (3 translations and 3 rotations). To take advantage of symmetry only one quarter of the pipe cross section was modeled. Appropriate boundary conditions were applied at the symmetry planes. As the pipe properties and the loading don't change in the pipe longitudinal direction only a small portion of the pipe length was discretized. The shell FE model was considered to be 8 mm long in order to have four elements, 2 mm long, between the two longitudinal boundaries of the FE model in which appropriate boundary conditions were applied to simulate a plane strain condition. The dimension of the shell elements in the circumferential direction was established pursuing an aspect ratio approximately equal to the unity.

Table 5 presents the basic geometric and material data of the 9 thinnest pipes ($D_e / t > 45$) that were discretized by shell FE models.

As an illustration, Figure 8 presents the frontal view of the shell FE mesh of the pipe LT60.0 with an initial ovalization equal to 4% while Figure 9 presents the lateral view of the same shell FE mesh. As an ovalization of 4% is too small to be perceived in a true scale plot the initial out-of-roundness was amplified in the plot shown in Figure 8.

The shell FE mesh shown in Figure 8 is a surface that coincides with the pipe mid-surface. Traditionally this is a characteristic of shell FE meshes.

Table 6 presents the collapse pressures of the 9 thinnest pipes ($D_e / t > 45$) which were predicted by the shell FE models.

Table 5 – Basic geometric and material data of the 9 thinnest pipes (D_e / t > 45)

Pipe	t (mm)	D_e / t
LT50.0	9.14	50.0
LT60.0	7.62	60.0
LT80.0	5.71	80.0
LT100.0	4.57	100.0
LT120.0	3.81	119.9
LT150.0	3.05	149.8
LT200.0	2.29	199.6
LT250.0	1.83	249.7
LT300.0	1.52	300.7
D_e = 457 mm		
API 5L X65 steel		
SMYS = 448 MPa		
E = 200000 MPa		
ν = 0.3		

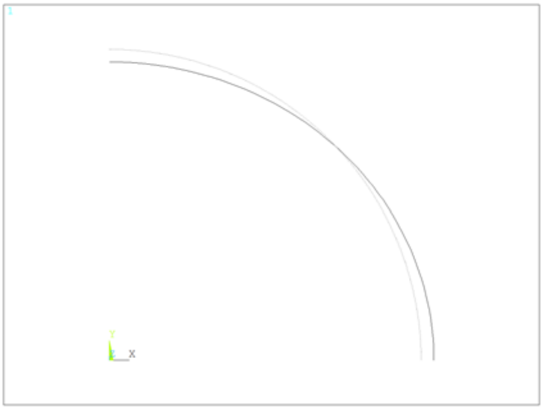

Figure 8 – Frontal view of the shell FE mesh of the pipe LT60.0 with initial ovalization equal to 4% (out of scale)

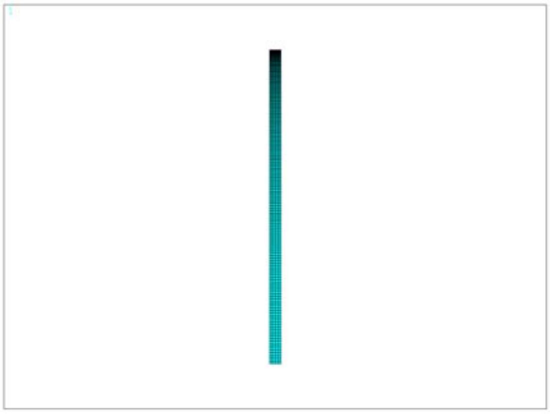

Figure 9 – Lateral view of the shell FE mesh of the pipe LT60.0 with initial ovalization equal to 4% (out of scale)

Table 6 – Collapse pressures of the 9 thinnest pipes predicted by the shell FE models

Pipe	$(p_{hc})_{FE}$ (MPa)				
	f_o = 0.0025	f_o = 0.0050	f_o = 0.01	f_o = 0.02	f_o = 0.04
LT50.0	3.59000	3.46000	3.24000	2.94000	2.50000
LT60.0	2.08000	2.02000	1.91000	1.75000	1.51000
LT80.0	0.87000	0.85000	0.82000	0.76000	0.68000
LT100.0	0.44700	0.44000	0.42600	0.40200	0.36200
LT120.0	0.25920	0.25560	0.24900	0.23690	0.21670
LT150.0	0.13320	0.13180	0.12900	0.12390	0.11520
LT200.0	0.05670	0.05630	0.05540	0.05376	0.05090
LT250.0	0.02921	0.02903	0.02867	0.02802	0.02682
LT300.0	0.01694	0.01686	0.01670	0.01640	0.01584

7 COLLAPSE PRESSURES OF THE THIRTEEN THICKEST PIPES PREDICTED BY THE COLLAPSE CHECKING METHODS

As mentioned earlier the RCA method was originally developed to be a collapse checking method [1] and afterwards it was chosen to be the reference method of the version 1 of the BCA method [3].

In this section the DNV method, the RCA V1 method and the RCA V2 method will be evaluated as collapse checking methods.

It is generally accepted that the applicable range of collapse checking methods should encompass pipelines whose D_e / t ratios are smaller than or equal to 45 ($D_e / t \leq 45$). In this range of D_e / t ratios, the collapse checking method should be conservative and should predict collapse pressures as accurate as possible.

Assuming that the collapse pressures contained in the RCA V2 database of nonlinear Finite Element (FE) analyses are the most accurate, the accuracy of the collapse checking methods will be proved in this section.

Tables 7 to 9 present the ratio of the collapse pressure $(p_{hc})_{\text{method}}$ predicted by the collapse checking method to the collapse pressure $(p_{hc})_{\text{FE}}$ predicted by the solid FE model, for the 13 thickest pipes. The same data is presented in Figures 10 to 14. The maximum of accuracy that one method could achieve would be a ratio $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}}$ equal to the unity. Realizing that maximum accuracy is not achieved by all collapse pressure predictions, four classes of conservatism and two classes of unconservatism were adopted. These classes and the different colors associated with them are described below.

- if $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 0.7$ the prediction is overly conservative and is presented in orange (■) in Tables 7 to 9.
- if $0.7 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 0.85$ the prediction is highly conservative and is presented in black (■) in Tables 7 to 9.
- if $0.85 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 0.95$ the prediction is moderately conservative and is presented in green (■) in Tables 7 to 9.
- if $0.95 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 1$ the prediction is slightly conservative and is presented in blue (■) in Tables 7 to 9.
- if $1 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 1.05$ the prediction is moderately unconservative and is presented in brown (■) in Tables 7 to 9.
- if $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} > 1.05$ the prediction is highly unconservative and would be presented in red (■) in Tables 7 to 9 if there were any.

The minimum and the maximum values of the collapse pressures predicted by the DNV method are equal to $0.6846\,(p_{hc})_{\text{FE}}$ and $1.0121\,(p_{hc})_{\text{FE}}$, respectively ($0.6846\,(p_{hc})_{\text{FE}} \leq (p_{hc})_{\text{DNV}} \leq 1.0121\,(p_{hc})_{\text{FE}}$).

The minimum and the maximum values of the collapse pressures predicted by the RCA V1 method are equal to $0.8649\,(p_{hc})_{\text{FE}}$ and $1.004\,(p_{hc})_{\text{FE}}$, respectively ($0.8649\,(p_{hc})_{\text{FE}} \leq (p_{hc})_{\text{RCA V1}} \leq 1.004\,(p_{hc})_{\text{FE}}$).

The minimum and the maximum values of the collapse pressures predicted by the RCA V2 method are equal to $0.8649\,(p_{hc})_{\text{FE}}$ and $1.0052\,(p_{hc})_{\text{FE}}$, respectively ($0.8649\,(p_{hc})_{\text{FE}} \leq (p_{hc})_{\text{RCA V1}} \leq 1.0052\,(p_{hc})_{\text{FE}}$).

Nine of the 65 collapse pressures predicted by the DNV method are greater than 1.0 $(p_{hc})_{\mathrm{FE}}$ and equal to or smaller than 1.0121 $(p_{hc})_{\mathrm{FE}}$. This unconservatism is negligibly small and requires no corrective action.

Eleven of the 65 collapse pressures predicted by the RCA V1 method are greater than 1.0 $(p_{hc})_{\mathrm{FE}}$ and equal to or smaller than 1.004 $(p_{hc})_{\mathrm{FE}}$. This unconservatism is negligibly small and requires no corrective action.

Fifteen of the 65 collapse pressures predicted by the RCA V2 method are greater than 1.0 $(p_{hc})_{\mathrm{FE}}$ and smaller than 1.0052 $(p_{hc})_{\mathrm{FE}}$. This unconservatism is negligibly small and requires no corrective action.

Considering Tables 7 to 9, Figures 10 to 14 and the paragraphs above, it is concluded that, for D_e / t ratios smaller than or equal to 45, the DNV method predictions, the RCA V1 method predictions and the RCA V2 method predictions are conservative.

The errors of the collapse checking methods predictions are presented in Tables 10 to 12.

Table 13 and Figure 15 present the mean errors of the collapse checking methods predictions calculated considering the lines of Tables 7, 8 and 9, i.e. taking from the lines associated to each of the 13 pipes five errors correspondent to the predictions of the method for each pipe with five different values of ovality. In the last line of this table it is presented the overall mean error, calculated considering the mean errors presented in the columns of this same table.

As can be seen in Figure 15, the mean errors of the collapse checking methods predictions for each tube with five different values of ovality become increasingly larger for D_e / t ratios smaller than 20. However the increase in the mean error of the DNV method predictions is much greater than the increase in the mean error of the RCA V1 method predictions which is slightly greater than the increase in the mean error of the RCA V2 method predictions.

Considering the overall mean error (last line of Table 15), the RCA V2 method is the method that predicted the collapse pressures closest to the collapse pressures predicted by the FE models. The RCA V2 method presented the smallest overall mean error (2.1%), followed by the RCA V1 method (3.3%) and the DNV method (8.6%).

Table 7 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratio for the 13 thickest pipes with ovality parameter f_o equal to 0.0025 and 0.005

Pipe	f_o = 0.0025			f_o = 0.0050		
	$\frac{(p_{hc})_{\text{DNV}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V1}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V2}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{DNV}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V1}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V2}}}{(p_{hc})_{\text{FE}}}$
LT05.0	0.6874	0.8649	0.8649	0.6884	0.8719	0.8719
LT07.5	0.7722	0.8980	0.9004	0.7749	0.9108	0.9124
LT10.0	0.8191	0.9134	0.9244	0.8230	0.9321	0.9386
LT12.5	0.8551	0.9224	0.9504	0.8614	0.9500	0.9642
LT15.0	0.8881	0.9265	0.9800	0.8964	0.9658	0.9863
LT17.5	0.9198	0.9249	1.0021	0.9310	0.9811	0.9998
LT20.0	0.9486	0.9177	1.0023	0.9615	0.9942	1.0028
LT22.5	0.9606	0.9129	1.0032	0.9763	1.0006	1.0016
LT25.0	0.9550	0.9151	1.0048	0.9764	1.0012	0.9996
LT30.0	0.9433	0.9286	1.0012	0.9669	0.9980	0.9960
LT35.0	0.9437	0.9427	0.9990	0.9610	0.9969	0.9949
LT40.0	0.9442	0.9528	0.9971	0.9595	0.9985	0.9940
LT45.0	0.9466	0.9630	0.9959	0.9594	1.0021	0.9957

Table 8 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratio for the 13 thickest pipes with ovality parameter f_o equal to 0.01 and 0.02

Pipe	f_o = 0.01			f_o = 0.02		
	$\frac{(p_{hc})_{\text{DNV}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V1}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V2}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{DNV}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V1}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V2}}}{(p_{hc})_{\text{FE}}}$
LT05.0	0.6886	0.8837	0.8836	0.6877	0.9060	0.9060
LT07.5	0.7772	0.9282	0.9325	0.7806	0.9552	0.9581
LT10.0	0.8290	0.9530	0.9662	0.8384	0.9810	0.9813
LT12.5	0.8720	0.9714	0.9927	0.8877	0.9971	0.9921
LT15.0	0.9123	0.9852	1.0028	0.9315	1.0040	0.9947
LT17.5	0.9499	0.9947	1.0020	0.9678	1.0034	0.9943
LT20.0	0.9794	0.9980	1.0009	0.9936	0.9976	0.9929
LT22.5	0.9945	0.9960	0.9993	1.0069	0.9900	0.9922
LT25.0	1.0000	0.9944	0.9986	1.0121	0.9835	0.9923
LT30.0	0.9911	0.9875	0.9904	1.0095	0.9784	0.9965
LT35.0	0.9722	0.9778	0.9778	1.0039	0.9818	1.0000
LT40.0	0.9805	0.9951	0.9919	1.0000	0.9889	1.0018
LT45.0	0.9771	1.0023	0.9931	0.9974	1.0026	1.0052

Table 9 – $(p_{hc})_{method}$ / $(p_{hc})_{FE}$ ratio for the 13 thickest pipes with ovality parameter f_o equal to 0.04

Pipe	$f_o = 0.04$		
	$\frac{(p_{hc})_{DNV}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V1}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V2}}{(p_{hc})_{FE}}$
LT05.0	0.6846	0.9502	0.9502
LT07.5	0.7834	0.9765	0.9758
LT10.0	0.8477	0.9818	0.9805
LT12.5	0.8995	0.9868	0.9853
LT15.0	0.9398	0.9921	0.9909
LT17.5	0.9691	0.9974	0.9965
LT20.0	0.9881	1.0004	1.0000
LT22.5	0.9995	1.0022	1.0022
LT25.0	1.0048	1.0021	1.0028
LT30.0	1.0075	1.0011	1.0011
LT35.0	1.0063	1.0000	1.0000
LT40.0	1.0044	0.9978	0.9956
LT45.0	1.0031	0.9969	0.9969

Table 10 – Error of the collapse pressures predicted by the collapse checking methods for the 13 thickest pipes with ovality parameter f_o equal to 0.0025 and 0.005

Pipe	error (%)					
	$f_o = 0.0025$			$f_o = 0.0050$		
	DNV	RCA V1	RCA V2	DNV	RCA V1	RCA V2
LT05.0	-31.3	-13.5	-13.5	-31.2	-12.8	-12.8
LT07.5	-22.8	-10.2	-10.0	-22.5	-8.9	-8.8
LT10.0	-18.1	-8.7	-7.6	-17.7	-6.8	-6.1
LT12.5	-14.5	-7.8	-5.0	-13.9	-5.0	-3.6
LT15.0	-11.2	-7.4	-2.0	-10.4	-3.4	-1.4
LT17.5	-8.0	-7.5	0.2	-6.9	-1.9	0.0
LT20.0	-5.1	-8.2	0.2	-3.9	-0.6	0.3
LT22.5	-3.9	-8.7	0.3	-2.4	0.1	0.2
LT25.0	-4.5	-8.5	0.5	-2.4	0.1	0.0
LT30.0	-5.7	-7.1	0.1	-3.3	-0.2	-0.4
LT35.0	-5.6	-5.7	-0.1	-3.9	-0.3	-0.5
LT40.0	-5.6	-4.7	-0.3	-4.0	-0.1	-0.6
LT45.0	-5.3	-3.7	-0.4	-4.1	0.2	-0.4
mean	10.9	7.8	3.1	9.7	3.1	2.7
std deviation	8.2	2.4	4.3	8.7	4.0	3.9

Note 1: error = $(((p_{hc})_{method} - (p_{hc})_{FE}) / (p_{hc})_{FE})\ 100$

Note 2: mean = $(1/13)\ \Sigma\ |\text{error}|$

Note 3: std deviation = $\sqrt{(1/13) \sum (|\text{error}| - \text{mean})^2}$

Table 11 – Error of the collapse pressures predicted by the collapse checking methods for the 13 thickest pipes with ovality parameter f_o equal to 0.01 and 0.02

Pipe	error (%)					
	$f_o = 0.01$			$f_o = 0.02$		
	DNV	RCA V1	RCA V2	DNV	RCA V1	RCA V2
LT05.0	-31.1	-11.6	-11.6	-31.2	-9.4	-9.4
LT07.5	-22.3	-7.2	-6.7	-21.9	-4.5	-4.2
LT10.0	-17.1	-4.7	-3.4	-16.2	-1.9	-1.9
LT12.5	-12.8	-2.9	-0.7	-11.2	-0.3	-0.8
LT15.0	-8.8	-1.5	0.3	-6.9	0.4	-0.5
LT17.5	-5.0	-0.5	0.2	-3.2	0.3	-0.6
LT20.0	-2.1	-0.2	0.1	-0.6	-0.2	-0.7
LT22.5	-0.5	-0.4	-0.1	0.7	-1.0	-0.8
LT25.0	0.0	-0.6	-0.1	1.2	-1.6	-0.8
LT30.0	-0.9	-1.3	-1.0	1.0	-2.2	-0.3
LT35.0	-2.8	-2.2	-2.2	0.4	-1.8	0.0
LT40.0	-2.0	-0.5	-0.8	0.0	-1.1	0.2
LT45.0	-2.3	0.2	-0.7	-0.3	0.3	0.5
mean	8.3	2.6	2.2	7.3	1.9	1.6
std deviation	9.4	3.3	3.3	9.7	2.4	2.5

Note 1: error = ($((p_{hc})_{\text{method}} - (p_{hc})_{\text{FE}}) / (p_{hc})_{\text{FE}}$) 100

Note 2: mean = (1/13) Σ |error|

Note 3: std deviation = $\sqrt{(1/13)\sum(|\text{error}| - \text{mean})^2}$

Table 12 – Error of the collapse pressures predicted by the collapse checking methods for the 13 thickest pipes with ovality parameter f_o equal to 0.04

Pipe	error (%)		
	$f_o = 0.04$		
	DNV	RCA V1	RCA V2
LT05.0	-31.5	-5.0	-5.0
LT07.5	-21.7	-2.3	-2.4
LT10.0	-15.2	-1.8	-2.0
LT12.5	-10.0	-1.3	-1.5
LT15.0	-6.0	-0.8	-0.9
LT17.5	-3.1	-0.3	-0.4
LT20.0	-1.2	0.0	0.0
LT22.5	-0.1	0.2	0.2
LT25.0	0.5	0.2	0.3
LT30.0	0.8	0.1	0.1
LT35.0	0.6	0.0	0.0
LT40.0	0.4	-0.2	-0.4
LT45.0	0.3	-0.3	-0.3
mean	7.0	1.0	1.0
std deviation	9.6	1.4	1.4

Note 1: error = ($((p_{hc})_{\text{method}} - (p_{hc})_{\text{FE}}) / (p_{hc})_{\text{FE}}$) 100

Note 2: mean = (1/13) Σ |error|

Note 3: std deviation = $\sqrt{(1/13)\sum(|\text{error}| - \text{mean})^2}$

Table 13 – Mean errors of the collapse pressures predictions for each of the 13 thickest pipes with five different values of ovality

Pipe	D_e / t	mean error (%)		
		DNV	RCA V1	RCA V2
LT05.0	5.0	31.3	10.5	10.5
LT07.5	7.5	22.2	6.6	6.4
LT10.0	10.0	16.9	4.8	4.2
LT12.5	12.5	12.5	3.4	2.3
LT15.0	15.0	8.6	2.7	1.0
LT17.5	17.5	5.2	2.1	0.3
LT20.0	20.0	2.6	1.9	0.3
LT22.5	22.5	1.5	2.1	0.3
LT25.0	25.0	1.7	2.2	0.3
LT30.0	30.1	2.3	2.2	0.4
LT35.0	35.2	2.7	2.0	0.6
LT40.0	40.1	2.4	1.3	0.5
LT45.0	45.2	2.5	0.9	0.5
overall mean error		8.6	3.3	2.1

Note 1: mean error = (1/5) Σ |error|

Note 2: overall mean error = (1/13) Σ mean error

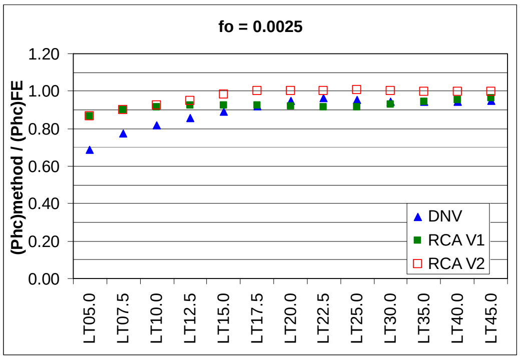

Figure 10 – $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}}$ ratios for $f_o = 0.0025$ for $5 \leq D_e / t \leq 45$

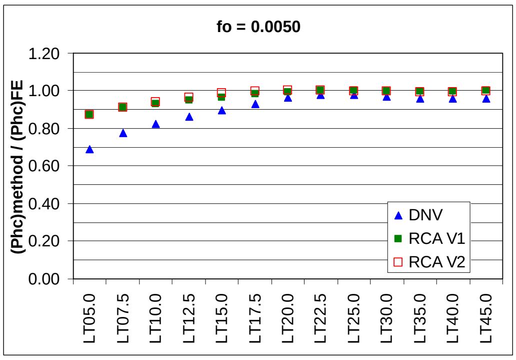

Figure 11 – $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}}$ ratios for $f_o = 0.005$ for $5 \leq D_e / t \leq 45$

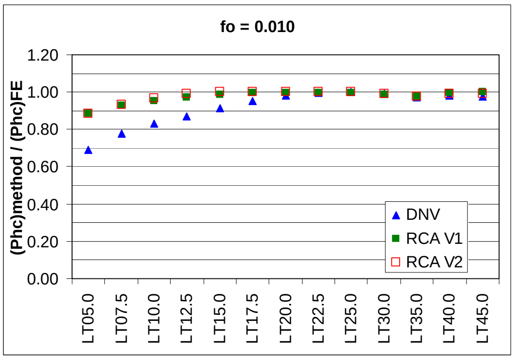

Figure 12 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.01$ for $5 \leq D_e / t \leq 45$

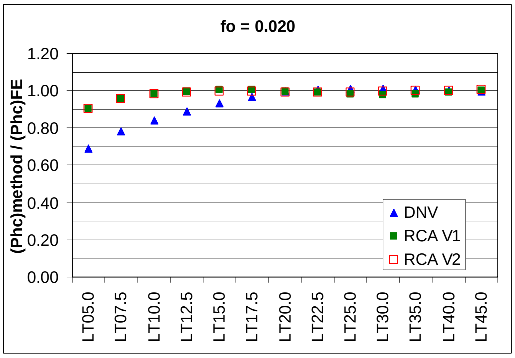

Figure 13 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.02$ for $5 \leq D_e / t \leq 45$

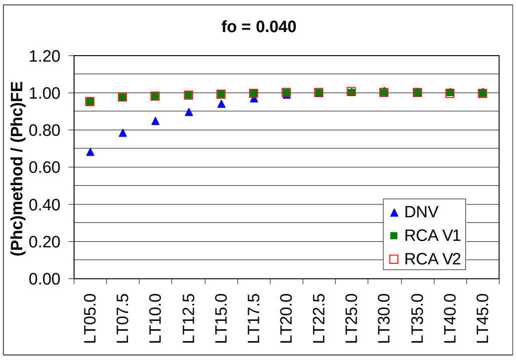

Figure 14 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.04$ for $5 \leq D_e / t \leq 45$

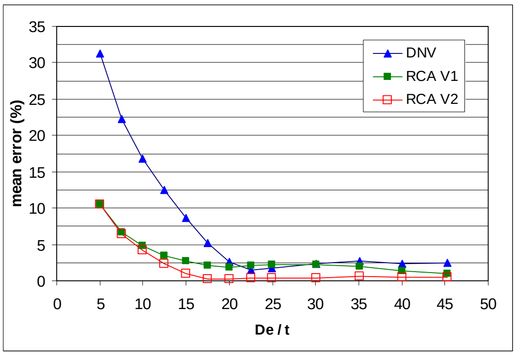

Figure 15 – Mean errors of the collapse checking method predictions for each of the thickest pipes with five different values of ovality

8 COLLAPSE PRESSURES OF THE NINE THINNEST PIPES PREDICTED BY THE REFERENCE METHODS

As mentioned earlier the RCA method was originally developed to be a collapse checking method [1] and afterwards it was chosen to be the reference method of the version 1 of the BCA method [3].

In this section the DNV method, the RCA V1 method and the RCA V2 method will be evaluated as reference methods.

It is assumed herein that if a collapse checking method is chosen to be a reference method its accuracy has already been proved for D_e / t ratios smaller than or equal to 45.

Within the framework of the BCA method the role of a reference method is to predict the collapse pressure $(p_{hc})_t$ of the uncorroded pipe and the collapse pressure $(p_{hc})_{t^*}$ of the uniformly corroded pipe with external diameter D_{t^*} and wall thickness t^* ($t^* = t - d$). It is not unlikely that a reference method may have to calculate the collapse pressure of a uniformly corroded pipe whose D_{t^*} / t^* ratio is greater than 45 and smaller than or equal to 300. In this range of D_{t^*} / t^* ratios, the reference method should be conservative and its conservatism should increase as the D_{t^*} / t^* ratio increases. The second recommendation is made because, as corrosion grows, not only the D_{t^*} / t^* ratio increases but also the wall thickness t^* diminishes. Depending on the pipeline cross section dimensions (external diameter D_e and wall thickness t), after enough time in operation, a corrosion defect may be so deep that the wall thickness t^* may approach 2 mm. As the wall thickness t^* becomes smaller the measurement uncertainty (associated with the sizing of the corrosion defect) [13] and the accuracy of the estimated corrosion growth rate become more important [13].

Assuming that the collapse pressures contained in the RCA V2 database of nonlinear Finite Element (FE) analyses are the most accurate, the level of conservatism of the reference methods will be proved in this section.

The ratios of the collapse pressure $(p_{hc})_{\text{method}}$ predicted by the reference method to the collapse pressure $(p_{hc})_{\text{FE}}$ predicted by the solid FE model are presented in Tables 14 to 16 and in Figures 16 to 20. The maximum of accuracy that one method could achieve would be a ratio $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}}$ equal to the unity. Realizing that maximum accuracy is not achieved by all collapse pressure predictions, four classes of conservatism and two classes of unconservatism were adopted. These classes and the different colors associated with them are described below.

- if $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 0.7$ the prediction is overly conservative and is presented in orange (■) in Tables 14 to 16.
- if $0.7 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 0.85$ the prediction is highly conservative and is presented in black (■) in Tables 14 to 16.
- if $0.85 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 0.95$ the prediction is moderately conservative and is presented in green (■) in Tables 14 to 16.
- if $0.95 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 1$ the prediction is slightly conservative and is presented in blue (■) in Tables 14 to 16.
- if $1 < (p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} \leq 1.05$ the prediction is moderately unconservative and is presented in brown (■) in Tables 14 to 16.
- if $(p_{hc})_{\text{method}} / (p_{hc})_{\text{FE}} > 1.05$ the prediction is highly unconservative and would be presented in red (■) in Tables 14 to 16.

The minimum and the maximum values of the collapse pressures predicted by the DNV method are equal to $0.9510\,(p_{hc})_{\text{FE}}$ and $1.0149\,(p_{hc})_{\text{FE}}$, respectively ($0.9510\,(p_{hc})_{\text{FE}} \leq (p_{hc})_{\text{DNV}} \leq 1.0149\,(p_{hc})_{\text{FE}}$).

The minimum and the maximum values of the collapse pressures predicted by the RCA V1 method are equal to $0.9646\,(p_{hc})_{\text{FE}}$ and $1.0686\,(p_{hc})_{\text{FE}}$, respectively ($0.9646\,(p_{hc})_{\text{FE}} \leq (p_{hc})_{\text{RCA V1}} \leq 1.0686\,(p_{hc})_{\text{FE}}$).

The minimum and the maximum values of the collapse pressures predicted by the RCA V2 method are equal to $0.8554\,(p_{hc})_{\text{FE}}$ and $1.0071\,(p_{hc})_{\text{FE}}$, respectively $0.8554\,(p_{hc})_{\text{FE}} \leq (p_{hc})_{\text{RCA V2}} \leq 1.0071\,(p_{hc})_{\text{FE}}$

Seven of the 45 collapse pressures predicted by the DNV method are greater than $1.0\,(p_{hc})_{\text{FE}}$ and equal to or smaller than $1.0149\,(p_{hc})_{\text{FE}}$. This unconservatism is negligibly small and requires no corrective action.

Twenty eight of the 45 collapse pressures predicted by the RCA V1 method are greater than 1.0 $(p_{hc})_{FE}$ and equal to or smaller than 1.048 $(p_{hc})_{FE}$. This unconservatism is not negligibly small. However it is small enough to be corrected by the usual safety factor.

Three of the 45 collapse pressures predicted by the RCA V1 method are greater than 1.05 $(p_{hc})_{FE}$ and equal to or smaller than 1.0686 $(p_{hc})_{FE}$. Although this unconservatism is high, it could be corrected by the use of an adequate safety factor. Even so it was deemed that a better approach would be to develop the RCA V2 method, a new version of the RCA method.

Twelve of the 45 collapse pressures predicted by the RCA V2 method are greater than 1.0 $(p_{hc})_{FE}$ and smaller than 1.0071 $(p_{hc})_{FE}$. This unconservatism is negligibly small and requires no corrective action.

Considering Tables 14 to 16, Figures 16 to 20 and the paragraphs above it is concluded that, for D_e / t ratios greater than 45 and smaller than or equal to 300, the DNV method predictions and the RCA V2 method predictions are conservative while the RCA V1 method predictions are unconservative.

Table 14 – $(p_{hc})_{method}$ / $(p_{hc})_{FE}$ ratio for the 9 thinnest pipes with ovality parameter f_o equal to 0.0025 and 0.005

Pipe	$f_o = 0.0025$			$f_o = 0.0050$		
	$\frac{(p_{hc})_{DNV}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V1}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V2}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{DNV}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V1}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V2}}{(p_{hc})_{FE}}$
LT50.0	0.9554	0.9749	1.0028	0.9682	1.0116	1.0029
LT60.0	0.9615	0.9904	1.0000	0.9703	1.0198	1.0050
LT80.0	0.9706	1.0084	1.0005	0.9786	1.0321	1.0042
LT100.0	0.9714	1.0087	0.9926	0.9750	1.0248	0.9905
LT120.0	0.9726	1.0062	0.9873	0.9765	1.0203	0.9836
LT150.0	0.9730	1.0008	0.9797	0.9757	1.0114	0.9727
LT200.0	0.9695	0.9903	0.9684	0.9703	0.9973	0.9563
LT250.0	0.9617	0.9781	0.9552	0.9628	0.9842	0.9411
LT300.0	0.9510	0.9646	0.9404	0.9514	0.9692	0.9235

Table 15 – $(p_{hc})_{method}$ / $(p_{hc})_{FE}$ ratio for the 9 thinnest pipes with ovality parameter f_o equal to 0.01 and 0.02

Pipe	$f_o = 0.01$			$f_o = 0.02$		
	$\frac{(p_{hc})_{DNV}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V1}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V2}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{DNV}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V1}}{(p_{hc})_{FE}}$	$\frac{(p_{hc})_{RCA\ V2}}{(p_{hc})_{FE}}$
LT50.0	0.9846	1.0185	1.0062	0.9966	1.0102	1.0034
LT60.0	0.9843	1.0314	1.0052	1.0000	1.0343	1.0057
LT80.0	0.9849	1.0480	0.9999	1.0045	1.0686	1.0071
LT100.0	0.9836	1.0465	0.9883	0.9955	1.0639	0.9925
LT120.0	0.9827	1.0398	0.9783	0.9937	1.0578	0.9844
LT150.0	0.9806	1.0279	0.9651	0.9895	1.0444	0.9709
LT200.0	0.9744	1.0099	0.9444	0.9805	1.0231	0.9449
LT250.0	0.9655	0.9937	0.9236	0.9693	1.0043	0.9176
LT300.0	0.9527	0.9760	0.9006	0.9549	0.9848	0.8878

Table 16 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratio for the 9 thinnest pipes with ovality parameter f_o equal to 0.04

Pipe	$f_o = 0.04$		
	$\frac{(p_{hc})_{\text{DNV}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V1}}}{(p_{hc})_{\text{FE}}}$	$\frac{(p_{hc})_{\text{RCA V2}}}{(p_{hc})_{\text{FE}}}$
LT50.0	1.0040	1.0000	0.9960
LT60.0	1.0132	1.0132	1.0066
LT80.0	1.0119	1.0149	0.9975
LT100.0	1.0149	1.0215	0.9934
LT120.0	1.0102	1.0194	0.9806
LT150.0	1.0026	1.0156	0.9601
LT200.0	0.9892	1.0055	0.9251
LT250.0	0.9758	0.9940	0.8911
LT300.0	0.9583	0.9785	0.8554

The errors of the reference methods predictions are presented in Tables 17 to 19.

Table 20 and Figure 21 present the mean errors of the reference methods predictions calculated considering the lines of Tables 14, 15 and 16, i.e. taking from the lines associated to each of the 9 pipes five errors correspondent to the predictions of the method for each pipe with five different values of ovality.

As can be seen in Figure 21 each of the curves of the mean errors has a particular shape.

The curve of the DNV method is composed of two parts. The first part starts at a point whose coordinates are (50.0 , 2.0) and ends at a point whose coordinates are (119.9 , 1.7). This part encompasses 5 points, that are irregularly distributed around an imaginary horizontal line whose ordinate is 1.8. The second part starts at the ending point of the first part and ends at a point whose coordinates are (300.7 , 4.6). This part is an increasing function of D_e / t and encompasses 5 points. Consequently, the requirement of increasing level of conservatism with increasing $D_{t*} / t*$ ratio is met at the second part of the DNV method curve which encompass 5 of the 9 points of the curve.

The curve of the RCA V1 method is composed of two half waves. The first half wave, which is concave downward, starts at a point whose coordinates are (50.0 , 1.3) and ends at a point whose coordinates are (149.8 , 2.0). The second half wave, which is concave upward, starts at the ending point of the first half wave and ends at a point whose coordinates are (300.7 , 2.5). Consequently, the requirement of increasing level of conservatism with increasing $D_{t*} / t*$ ratio is not met at any part of the RCA V1 method curve.

The curve of the RCA V2 method is composed of two parts. The first part starts at a point whose coordinates are (50.0 , 0.4) and ends at a point whose coordinates are (80.0 , 0.3). This part encompasses 3 points, that are irregularly distributed around an imaginary horizontal line whose ordinate is 0.4. The second part starts at the ending point of the first part and ends at a point whose coordinates are (300.7 , 9.8). This part is an increasing function of D_e / t and encompasses 7 points. Consequently, the requirement of increasing level of conservatism with increasing $D_{t*} / t*$ ratio is met at the second part of the RCA V2 method curve which encompass 7 of the 9 points of the curve.

Considering Table 20, Figure 21 and the paragraphs above it is concluded that the RCA V2 method is the first reference method that comes close to meeting the requirement of increasing level of conservatism with increasing $D_{t*} / t*$ ratio and the DNV method is the second reference method that comes close to meeting this requirement. The RCA V1 method does not meet this requirement.

Table 17 – Error of the collapse pressures predicted by the reference methods for the 9 thinnest pipes with ovality parameter f_o equal to 0.0025 and 0.005

Pipe	error (%)					
	f_o = 0.0025			f_o = 0.0050		
	DNV	RCA V1	RCA V2	DNV	RCA V1	RCA V2
LT50.0	-4.5	-2.5	0.3	-3.2	1.2	0.3
LT60.0	-3.8	-1.0	0.0	-3.0	2.0	0.5
LT80.0	-2.9	0.8	0.0	-2.1	3.2	0.4
LT100.0	-2.9	0.9	-0.7	-2.5	2.5	-1.0
LT120.0	-2.7	0.6	-1.3	-2.3	2.0	-1.6
LT150.0	-2.7	0.1	-2.0	-2.4	1.1	-2.7
LT200.0	-3.1	-1.0	-3.2	-3.0	-0.3	-4.4
LT250.0	-3.8	-2.2	-4.5	-3.7	-1.6	-5.9
LT300.0	-4.9	-3.5	-6.0	-4.9	-3.1	-7.7
mean	3.5	1.4	2.0	3.0	1.9	2.7
std deviation	0.8	1.0	2.0	0.8	0.9	2.5

Note 1: error = $(((p_{hc})_{\text{method}} - (p_{hc})_{\text{FE}}) / (p_{hc})_{\text{FE}}) 100$
Note 2: mean = $(1/9) \Sigma |\text{error}|$
Note 3: std deviation = $\sqrt{(1/9) \sum (|\text{error}| - \text{mean})^2}$

Table 18 – Error of the collapse pressures predicted by the reference methods for the 9 thinnest pipes with ovality parameter f_o equal to 0.0025 and 0.005

Pipe	error (%)					
	f_o = 0.01			f_o = 0.02		
	DNV	RCA V1	RCA V2	DNV	RCA V1	RCA V2
LT50.0	-1.5	1.9	0.6	-0.3	1.0	0.3
LT60.0	-1.6	3.1	0.5	0.0	3.4	0.6
LT80.0	-1.5	4.8	0.0	0.4	6.9	0.7
LT100.0	-1.6	4.6	-1.2	-0.4	6.4	-0.7
LT120.0	-1.7	4.0	-2.2	-0.6	5.8	-1.6
LT150.0	-1.9	2.8	-3.5	-1.0	4.4	-2.9
LT200.0	-2.6	1.0	-5.6	-2.0	2.3	-5.5
LT250.0	-3.5	-0.6	-7.6	-3.1	0.4	-8.2
LT300.0	-4.7	-2.4	-9.9	-4.5	-1.5	-11.2
mean	2.3	2.8	3.5	1.4	3.6	3.5
std deviation	1.1	1.4	3.3	1.4	2.3	3.7

Note 1: error = $(((p_{hc})_{\text{method}} - (p_{hc})_{\text{FE}}) / (p_{hc})_{\text{FE}}) 100$
Note 2: mean = $(1/9) \Sigma |\text{error}|$
Note 3: std deviation = $\sqrt{(1/9) \sum (|\text{error}| - \text{mean})^2}$

Table 19 – Error of the collapse pressures predicted by the reference methods for the 9 thinnest pipes with ovality parameter f_o equal to 0.04

Pipe	error (%)		
	$f_o = 0.04$		
	DNV	RCA V1	RCA V2
LT50.0	0.4	0.0	-0.4
LT60.0	1.3	1.3	0.7
LT80.0	1.2	1.5	-0.3
LT100.0	1.5	2.2	-0.7
LT120.0	1.0	1.9	-1.9
LT150.0	0.3	1.6	-4.0
LT200.0	-1.1	0.6	-7.5
LT250.0	-2.4	-0.6	-10.9
LT300.0	-4.2	-2.1	-14.5
mean	1.5	1.3	4.5
std deviation	1.1	0.7	4.9

Note 1: error = ($((p_{hc})_{\text{method}} - (p_{hc})_{\text{FE}}) / (p_{hc})_{\text{FE}}$) 100

Note 2: mean = (1/9) Σ |error|

Note 3: std deviation = $\sqrt{(1/9)\sum(|\text{error}| - \text{mean})^2}$

Table 20 – Mean errors of the collapse pressures predictions for each of the 9 thinnest pipes with five different values of ovality

Pipe	DNV		RCA V1		RCA V2	
	D_e / t	mean error (%)	D_e / t	mean error (%)	D_e / t	mean error (%)
LT50.0	50.0	2.0	50.0	1.3	50.0	0.4
LT60.0	60.0	1.9	60.0	2.2	60.0	0.5
LT80.0	80.0	1.6	80.0	3.4	80.0	0.3
LT100.0	100.0	1.8	100.0	3.3	100.0	0.9
LT120.0	119.9	1.7	119.9	2.9	119.9	1.7
LT150.0	149.8	1.7	149.8	2.0	149.8	3.0
LT200.0	199.6	2.3	199.6	1.0	199.6	5.2
LT250.0	249.7	3.3	249.7	1.1	249.7	7.4
LT300.0	300.7	4.6	300.7	2.5	300.7	9.8

Note 1: mean error = (1/5) Σ |error|

Note 2: Green color identifies the starting point of the first part of the curve

Note 3: Yellow color identifies the ending point of the first part of the curve and the starting point of the second part of the curve

Note 4: Orange color identifies the ending point of the second part of the curve

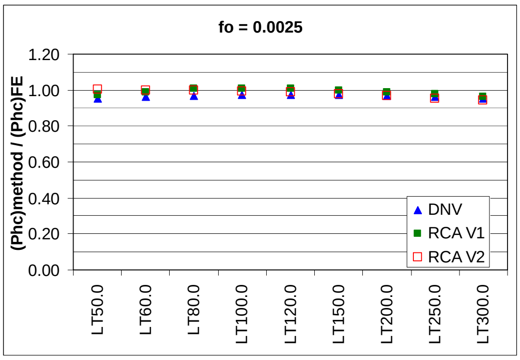

Figure 16 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.0025$ for $45 < D_e / t \leq 300$

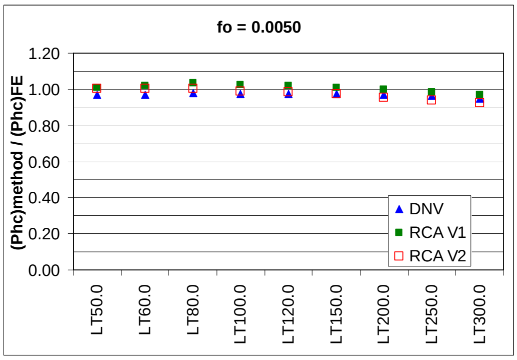

Figure 17 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.005$ for $45 < D_e / t \leq 300$

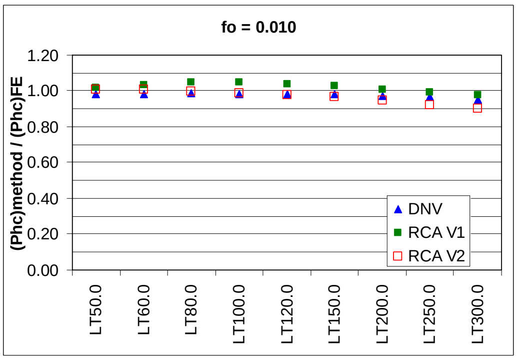

Figure 18 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.01$ for $45 < D_e / t \leq 300$

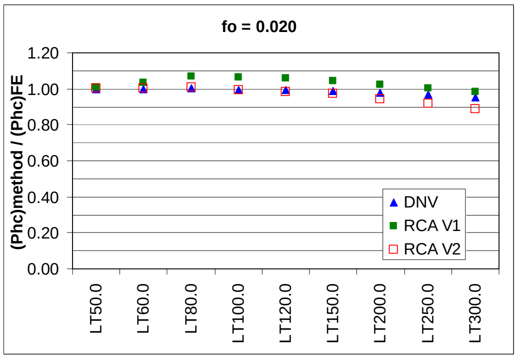

Figure 19 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.02$ for $45 < D_e / t \leq 300$

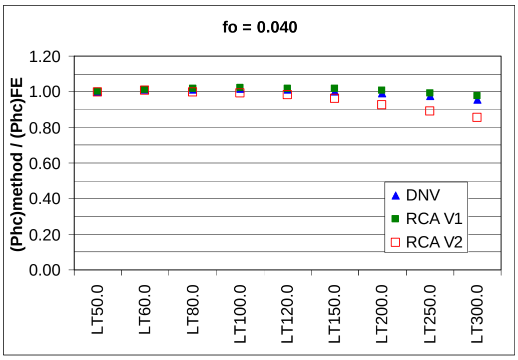

Figure 20 – $(p_{hc})_{\text{method}}$ / $(p_{hc})_{\text{FE}}$ ratios for $f_o = 0.04$ for $45 < D_e / t \leq 300$

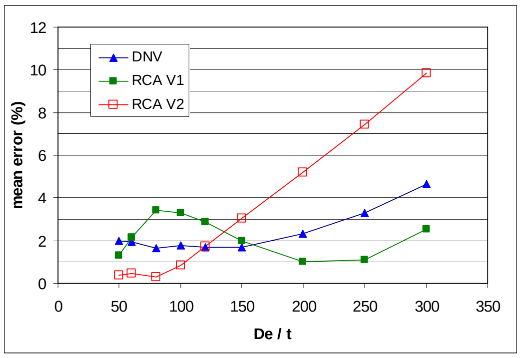

Figure 21 – Mean errors of the reference method predictions for each of the 9 thinnest pipes with five different values of ovality

9 CONCLUSIONS

In this paper the RCA V2 method, a new method for the prediction of the hydrostatic collapse pressure of submarine pipelines, was presented. The development of this method was based on the hydrostatic collapse pressures contained in the RCA V2 database.

The RCA V2 database contains a set of nonlinear Finite Element (FE) analyses of 22 infinitely long plain pipes. Each of the 22 pipes has an external diameter equal to 457 mm (18 in) and an external diameter to thickness ratio (D_e / t) which varies from 5 to 300. The only geometric imperfection considered is the ovalization of the pipe cross section, characterized by the ovality parameter f_o, which, for each pipe, has the following values: 0.0025, 0.005, 0.01, 0.02 and 0.04. As five FE analyses were carried out for each pipe, in total there are 110 FE analyses in the RCA V2 database.

Besides the RCA V2 method two other methods for the prediction of the hydrostatic collapse pressure of submarine pipelines were addressed: namely the DNV method and the RCA V1 method.

Assuming that the collapse pressures contained in the RCA V2 database of nonlinear Finite Element (FE) analyses are the most accurate, the performance of the three selected methods was evaluated. This evaluation was carried out by means of the comparison of the collapse pressure $(p_{hc})_{\text{method}}$ predicted by the reference method with the collapse pressure $(p_{hc})_{\text{FE}}$ predicted by the solid FE model.

It is generally accepted that the applicable range of collapse checking methods should encompass pipelines whose D_e / t ratios are smaller than or equal to 45. In this range of D_e / t ratios, the collapse checking method should be conservative and should predict collapse pressures as accurate as possible.

In section 7, considering only the 13 thickest pipes among the 22 pipes contained in the RCA V2 database, the three selected methods were evaluated as collapse checking methods.

The minimum and the maximum values of the collapse pressures predicted by the DNV method are equal to 0.6846 $(p_{hc})_{\text{FE}}$ and 1.0121 $(p_{hc})_{\text{FE}}$, respectively.

The minimum and the maximum values of the collapse pressures predicted by the RCA V1 method are equal to 0.8649 $(p_{hc})_{\text{FE}}$ and 1.004 $(p_{hc})_{\text{FE}}$, respectively.

The minimum and the maximum values of the collapse pressures predicted by the RCA V2 method are equal to 0.8649 $(p_{hc})_{\text{FE}}$ and 1.0052 $(p_{hc})_{\text{FE}}$, respectively.

It is concluded that, for D_e / t ratios smaller than or equal to 45, the DNV method predictions, the RCA V1 method predictions and the RCA V2 method predictions are conservative.

As can be seen in Figure 15, the mean errors of the collapse checking methods predictions for each tube with five different values of ovality become increasingly larger for D_e / t ratios smaller than 20. However the increase in the mean error of the DNV method predictions is much greater than the increase in the mean error of the RCA V1 method predictions which is slightly greater than the increase in the mean error of the RCA V2 method predictions.

Considering the overall mean error (last line of Table 15), the RCA V2 method is the method that predicted the collapse pressures closest to the collapse pressures predicted by the

FE models. The RCA V2 method presented the smallest overall mean error (2.1%), followed by the RCA V1 method (3.3%) and the DNV method (8.6%).

It is assumed herein that if a collapse checking method is chosen to be a reference method its accuracy has already been proved for D_e / t ratios smaller than or equal to 45 ($D_e / t \leq 45$). Then it is necessary to evaluate the performance of this method only for D_e / t ratios greater than 45 and smaller than or equal to 300 ($45 < D_e / t \leq 300$). In this range of D_e / t ratios, the reference method should be conservative and its conservatism should increase as the D_e / t ratio increases.

In section 8, considering only the 9 thinnest pipes among the 22 pipes contained in the RCA V2 database, the three selected methods were evaluated as reference methods.

The minimum and the maximum values of the collapse pressures predicted by the DNV method are equal to 0.9510 $(p_{hc})_{\mathrm{FE}}$ and 1.0149 $(p_{hc})_{\mathrm{FE}}$, respectively.

The minimum and the maximum values of the collapse pressures predicted by the RCA V1 method are equal to 0.9646 $(p_{hc})_{\mathrm{FE}}$ and 1.0686 $(p_{hc})_{\mathrm{FE}}$, respectively.

The minimum and the maximum values of the collapse pressures predicted by the RCA V2 method are equal to 0.8554 $(p_{hc})_{\mathrm{FE}}$ and 1.0071 $(p_{hc})_{\mathrm{FE}}$, respectively.

It is concluded that, for D_e / t ratios greater than 45 and smaller than or equal to 300, the DNV method predictions and the RCA V2 method predictions are conservative while the RCA V1 method predictions are unconservative.

Figure 21 presents curves of the mean errors of the methods predictions. As can be seen in this figure each of these curves has a particular shape.

The curve of the DNV method is composed of two parts. The first part encompasses 5 points that are irregularly distributed around an imaginary horizontal line whose ordinate is 1.8. The second part is an increasing function of D_e / t and encompasses 5 points. Consequently, the requirement of increasing level of conservatism with increasing D_{t^*} / t^* ratio is met at the second part of the DNV method curve which encompass 5 of the 9 points of the curve.

The curve of the RCA V1 method is composed of two half waves. Consequently, the requirement of increasing level of conservatism with increasing D_{t^*} / t^* ratio is not met at any part of the RCA V1 method curve.

The curve of the RCA V2 method is composed of two parts. The first part encompasses 3 points that are irregularly distributed around an imaginary horizontal line whose ordinate is 0.4. The second part is an increasing function of D_e / t and encompasses 7 points. Consequently, the requirement of increasing level of conservatism with increasing D_{t^*} / t^* ratio is met at the second part of the RCA V2 method curve which encompass 7 of the 9 points of the curve.

It is concluded that the RCA V2 method is the first reference method that come close to meeting the requirement of increasing level of conservatism with increasing D_{t^*} / t^* ratio and the DNV method is the second reference method that come close to meeting this requirement. The RCA V1 method does not meet this requirement.

The above conclusions are for a specific set of Finite Element results and must be confirmed for a large number of numerical and experimental results.

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