Visual Abstract

Prediction of the burst pressure for defective pipelines using different semi-empirical models

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ABSTRACT. The main aim of this work is to predict the theoretical burst pressure of defective pipelines using different semi-empirical models and compare them with the hydrostatic test results. A new methodology was formulated with accounting for a minimum thickness (weakest section of the pipe) over the length of the pipe to predict the most conservative burst pressure. With a simple analytical expression, a reasonable accuracy and more conservative burst pressure can be obtained for any arbitrary defect shapes. A variation of burst pressure was found between theoretical prediction and hydrostatic burst test results with respect to the different semi-empirical models even for the same corroded defects. Different defect geometry shape and pipe material conditions are the possible causes for variation in the burst pressure between the semi-empirical models, so a careful selection of these parameters is necessary. The proposed methodology predicted a more conservative burst pressure for all arbitrary defects shapes and can predict reasonably accurate values if it accounts for the axial stress.

KEYWORDS. Burst pressure; Metallic pipelines; Remaining strength; Pipeline corrosion; Empirical model; Corroded pipeline.

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INTRODUCTION

Metallic pipelines are extensively used to transport fluids (oil, gas, water) over a long distance, especially in the oil, gas and petroleum industries. Pipelines are exposed to harsh environmental conditions which lead to defects, such as metal-loss corrosion, gouges and stress corrosion cracking, etc. [1-4]. However, natural corrosion is the main source of damage in metallic pipelines and this process causes metal loss of the pipe. Both internal and external corrosion processes cause material reduction of the pipe and consequently decrease its strength capacity. If the strength capacity of a damaged pipe can sustain the designed burst pressure, then it can avoid incurring the cost of maintenance and repair [5]. Hence, an accurate and conservative theoretical prediction of burst pressure is an important issue, which would help to make a final call on whether the repair and maintenance can be postponed.

Theoretical prediction of the burst pressure of a corroded pipeline is of significant relevance to the gas and pipeline industry. Already, many semi-empirical models have been developed to predict the burst capacity of damage pipelines. There are many semi-empirical models which include: ASME B31G, modified ASME B31G, RSTRENG 0.85, SHELL92, DNV, PCORRC, Chell limit, Sims pressure and Ritchie, etc. to assess the durability condition of corroded pipelines [6-11]. The basic assumption of an empirical model is that the reduction of strength due to corrosion is corresponding to the amount of material loss measured along the length of the pipe. Generally, the defect region of the pipe is represented through a rectangle, elliptical, parabolic or mixed defect shape which is machined with depth interrelated to the greater corrosion depth measured along the pipe [12-17]. Hydrostatic burst tests are generally carried out on different metal wall loss defect geometries for assessing the structural integrity of these pipelines. Many researchers found a variation of theoretical prediction of burst pressure with respect to the different semi-empirical models even for the same defect area [11, 17-22]. Pipe material condition and empirical equation of remaining strength factor (defect geometry) are different in each model, which leads to a difference in theoretical burst pressure.

Still there is difference in the theoretical prediction and experimental burst pressure and this is due to certain assumptions while deriving the analytical model. For example, in a burst test, there is an axial stress induced as both the ends of the cylindrical tube are closed, however in the analysis it is neglected [18, 23]. In most of the semi-empirical model, defect width is not accounting in the analysis, but it effects on the prediction of burst pressure [24]. Real pipelines are long and the effect of axial stresses in straight lines is almost negligible (all criteria for corroded pipelines mentioned before neglect the effect of axial stresses), but that is not the case of the specimens for hydrostatic testing. A pipe specimen has a machined defect region with reduced wall thickness for a hydrostatic burst test and this makes a small variation between the actual corroded geometry region and the machined defect geometry of the test specimen. This assumption should be accounted for in the analysis for a better prediction of the burst pressure of a corroded pipeline.

The study of the burst pressure of corroded pipes is reasonably well developed, but still a very active area, as there is scope to refine the model with certain conditions. In the first part of this paper, validate the theoretical burst pressure obtained through different semi-empirical model with the hydrostatic burst pressure. In addition to that, this paper presents a methodology to estimate the burst pressure of pipelines with an arbitrary localized damage without accounting for the remaining strength factor. The minimum thickness of the pipe in its weakest part (corroded damage section) is considered in the analysis. Thus, it is expected to obtain a lower limit for the burst pressure of a metallic pipeline with an arbitrary localized corrosion defect. A total of 35 experimental burst tests carried out in different laboratories are compared with the proposed theoretical method for an assurance on the proposed model.

BURST PRESSURE

Defect free pipelines

The integrity of a pipeline is generally determined by the ability of the pipe to sustain the fluid pressure within the pipe. A Pipe fails when the stress in the pipe material exceeds its limit with the internal pressure increases and generally it comes into the plastic collapse stage (plastic deformation).

The Burst pressure of a defect free pipe is determined based on yield failure criteria such as Von Mises, Tresca or ASSY (Average Shear Stress Yield). The general form of the burst pressure can be expressed as follows [25, 26]:

$$P_b = \left(\frac{k}{2}\right)^{n+1} \frac{4t}{D}\sigma_{ult} \tag{1}$$

where, n is the strain hardening exponent which is material dependent and kis the material constant that depends on the yielding criterion as follows [25].

$$k = \begin{cases} 1 & Tresca \\ \dfrac{2}{\sqrt{3}} & ,Von\ Mises \\ \dfrac{1}{2} + \dfrac{1}{\sqrt{2}}, & ASSY. \end{cases}$$

The strain hardening exponent is determined based on the Hollomon (power-law) model [27] and the Ramberg-Osgood model [28] for failure analysis of pipeline.

Corroded pipelines
The basic model of the pipe to determine the theoretical burst pressure is extended to the corroded (damage/defect) metallic pipeline.
The general equation of the burst pressure for a pipeline with a corrosion defect is as follows:

$$P_{max}^{th} = \frac{t}{\alpha_\theta r_i} \sigma_{flow} \tag{2}$$

where the flow stress (σ_{flow}) represents the flow stress of the pipe material and α_θ is a remaining strength function (i.e. damage factor) which represents the strength reduction of the pipelines due to the corrosion.
There are many semi-empirical models available in the literature however a careful selection of the model is very important as both flow stress and remaining strength values differ with respect to the model.

REMAINING STRENGTH OF CORRODED PIPELINES

An accurate representation of defect geometry and defect shape of the damaged pipeline is useful for a better prediction of the remaining strength capacity of the pipe. Natural corrosion is the main source of localized damage of metallic pipelines, hence, defect size and shape is quite different from case to case. Generally, a non-uniform nature of corrosion occurs as shown in Fig 1(a) and to represent the actual defect shape for analysis is quite difficult. In most of the semi-empirical models (Tab. 1), the defect shapes are idealized as rectangular, parabolic, elliptical, mixed or effective area shape. Researchers often used a controlled metal wall loss using a machined process on a metal tube to replicate the actual corrosion defect and one such example is rectangular defect as shown in Fig 1(b) [12].

Figure 1: Metallic pipeline (a) with actual corroded defect [27] (b) machined defect to represent corroded damage [12].

Metal wall loss defects (rectangular, parabolic, etc.) in metallic pipelines are taken into account by the remaining strength factor (α_θ) for prediction of strength capacity of a corroded pipe.
The general form of strength prediction of defective pipelines is as:

$$\sigma_\theta = \alpha_\theta \left(\frac{P \cdot r_i}{t} \right)_{undamaged} \tag{3}$$

$$P_{max}^{th} = \frac{t}{\alpha_\theta \cdot r_i}\sigma_{flow} \quad (4)$$

Sr. No	Criteria	Damage factor/remaining strength	Bulging/Folias factor	Flow stress	Defect Shape
1	ASME B31G [6]	$If A_f \le 4,$ $\alpha_\theta = \frac{1-\frac{2}{3}\left(\frac{d}{t\sqrt{A_f^2+1}}\right)}{1-\frac{2}{3}\left(\frac{d}{t}\right)}$ $If A_f \le 4\ ,\ \ \alpha_\theta = \frac{t}{t-d}$	$A_f = 0.893\left(\frac{L}{\sqrt{D\cdot t}}\right)$	$\sigma_{flow} = 1.1\sigma_y$	Parabolic
2	RSTRENG 0.85 (Modified ASME B31G) [9]	$\alpha_\theta = \frac{1-0.85\left(\frac{d}{t}\right)\left(\frac{1}{M_t}\right)}{1-0.85\left(\frac{d}{t}\right)}$	$M_t = \sqrt{1+0.275\left(\frac{L^2}{D\cdot t}\right)-0.00375\left(\frac{L^2}{D\cdot t}\right)^2}$ $M_t = 3.3+0.032\left(\frac{L^2}{D\cdot t}\right)$	$\sigma_{flow} = \sigma_y + 69$	Effective area/length mixed
3	DNV [8]	$\alpha_\theta = \left[\frac{1-\left(\frac{d}{t}\right)\left(\frac{1}{Q}\right)}{1-\left(\frac{d}{t}\right)}\right]$	$Q = \sqrt{1+0.31\left(\frac{L^2}{D\cdot t}\right)}$	$\sigma_{flow} = \sigma_{ult}$	Rectan.
4	Ritchie and Last criterion [11]	$\alpha_\theta = \frac{1-\left(\frac{d}{t}\right)\left(\frac{1}{M_{t1}}\right)}{1-\left(\frac{d}{t}\right)}$	$M_t = \sqrt{1+0.8\left(\frac{L^2}{D\cdot t}\right)}$	$\sigma_{flow} = 0.9\sigma_{ult}$	Rectan.
5	PRC Battelle [11]	$\alpha_\theta = \left\{1-\frac{d}{t}\left[1-exp\left(-0.157\frac{L}{\sqrt{R(t-d)}}\right)\right]\right\}^{-1}$		$\sigma_{flow} = \sigma_{ult}$	Elliptical

Table 1: Damage factor (remaining strength) and flow stress equation of different criteria/model

There are many existing semi-empirical models available in the literature and the most widely used are listed in Tab.1 da Mattos et al. [11] found that the remaining strength factor value differs almost 50-80% with respect to different semi-empirical models for the same defect size on metallic pipelines. This is a large variation in the remaining strength factor value found for the same defect geometry and hence proper selection of the model is necessary, as per the area of application. Similarly, the flow stress value also differs with respect to the selection of the model (Tab. 1). However the flow stress value should be less than the ultimate strength of the pipe material ($\sigma_{flow} \le \sigma_{ult}$) for safe design. On the contrary, the flow stress exceeds the ultimate strength as per RSTRENG 0.85 criterion due to the high strength pipe metal having a very small difference in yield and ultimate strength [19]. Therefore, for a high strength metal pipe, it would be better to take the ultimate stress as the flow stress. In summary, the remaining strength factor and flow stress factor play an important role for predicting the burst pressure.

Tab. 2 summarizes the test results of 35 burst tests data using pipe specimens with machined different artificial metal losses (defects) [11, 19, 20, 24, 30-33] to demonstrate the suitability of the semi-empirical model for a better prediction of the strength capacity of defect pipe.

Sr. No (Ref.)	Material Grade	σ_y (MPa)	σ_{ult} (MPa)	D (mm)	t(mm)	d (mm)	L (mm)	P_{max}^{exp} (MPa)
1 [19]	X80	589	731	459	7.9	3	40	24.2
2 [19]	X80	601	684	457	7.9	4	40	22.7
3 [19]	X60	452	542	324	9.5	6.67	256	14.4
4 [19]	X46	391	458	76.2	2.04	1.4	75	9.4
5 [19]	A25	260	309	76.2	2	1.4	75	5.45
6 [19]	X60	452	542	324	9.5	6.67	306	14.07
7 [19]	X60	452	542	324	9.5	6.67	350	13.58
8 [19]	X60	452	542	324	9.5	6.67	395	12.84
9 [19]	X60	452	542	324	9.5	6.67	433	12.13
10 [19]	X60	452	542	324	9.5	6.67	467	11.92
11 [19]	X60	452	542	324	9.5	6.67	484	11.91
12 [19]	X60	452	542	324	9.5	6.67	500	11.99
13 [19]	X60	452	542	324	9.5	6.67	528	11.3
14 [30]	X80	601	684	458.8	8.1	5.39	39.6	22.68
15 [30]	X80	589	731	459.4	8.1	3.75	40.05	24.2
16 [20]	X42	380	528.5	273.8	5.30	2.52	1000	15.53
17 [20]	X42	380	528.5	273.7	5.24	2.04	1000	15.34
18 [20]	X46	357.9	458.2	456.5	6.56	3.32	2750	10.34
19 [20]	X46	355.7	539.2	457.7	6.23	3.27	2750	12.06
20 [20]	X46	362.3	557.3	457.1	6.09	2.8	2750	12.63
21 [20]	X46	285.1	428.5	457.7	6.04	2.71	2750	10.13
22 [20]	X46	345.4	568.2	457.7	6.03	2.79	2750	13.04
23 [31]	X65	495	565	762.0	17.50	8.75	50	27.50
24 [31]	X65	495	565	762.0	17.50	8.75	100	24.30
25 [31]	X65	495	565	762.0	17.50	8.75	200	21.80
26 [31]	X65	495	565	762.0	17.50	8.75	300	19.80
27 [31]	X65	495	565	762.0	17.50	8.75	600	18.50
28 [31]	X65	495	565	762.0	17.50	8.75	900	15.00
29 [32]	X70	532.2	628.8	762	15.9	7.95	300	21.2
30 [33]	Steel 20	305	585	219	6	3.6	133	13.8
31 [11]	X60	478	542	527	14.3	10	500	11.6
32 [24]	X42	284	464	60	5.80	4.1	49.7	54
33 [24]	X42	284	464	60	5.60	3.5	49.8	61
34 [24]	X42	284	464	60	5.55	4	69.7	46
35 [24]	X42	284	464	60	5.62	4.5	50	44

Table 2: Burst tests data

BURST PRESSURE PREDICTION USING SEMI-EMPIRICAL MODELS

Figs. 2 and 3 present the ratio between the predicted burst pressure and the experimental burst pressure ($P_{theoretical}/P_{experimental}$) using the different semi-empirical models. The results shows a mixed trend (conservative/non conservative/accurate) of burst pressure values between predicted and experimental with respect to the different semi empirical models. Some models show conservative predictions of burst pressure, while others show more accurate predictions of the burst pressure. There is quite a significant variation of the theoretical burst pressure between the different semi-empirical models for the same test specimen. This is related to the assumptions of remaining strength function (α_θ) and flow stress material (σ_{flow}), which leads to a variation in burst pressure even for the same defect pipe.In most of the semi empirical model the defect width in pipeline is not accounted, however some results found the influence of width on final burst pressure [9, 24,34]. In addition to that the complicated geometry of corroded region to represent in analysis is quite complicated and leads in the variation in experimental and theoretical results. Hence, defect geometry shape, size and other dimensions of pipeline need to be accounted when the semi-empirical model is selected.

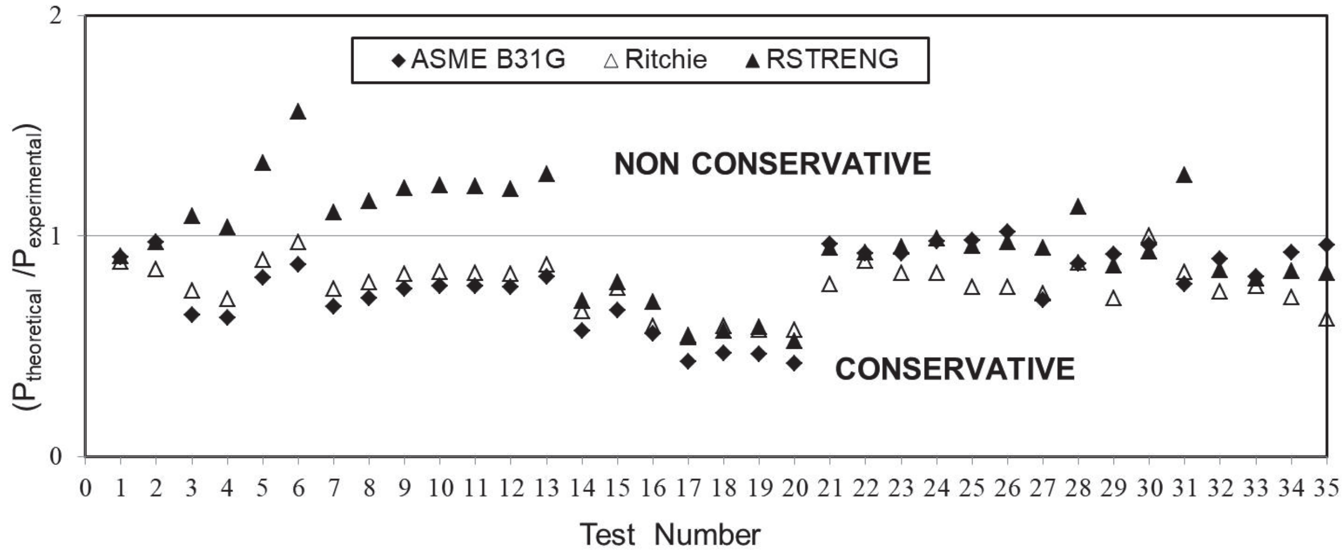

Figure2: ($P_{theoretical}/P_{experimental}$) per test with conservative and non-conservative burst pressure using selected semi-empirical model.

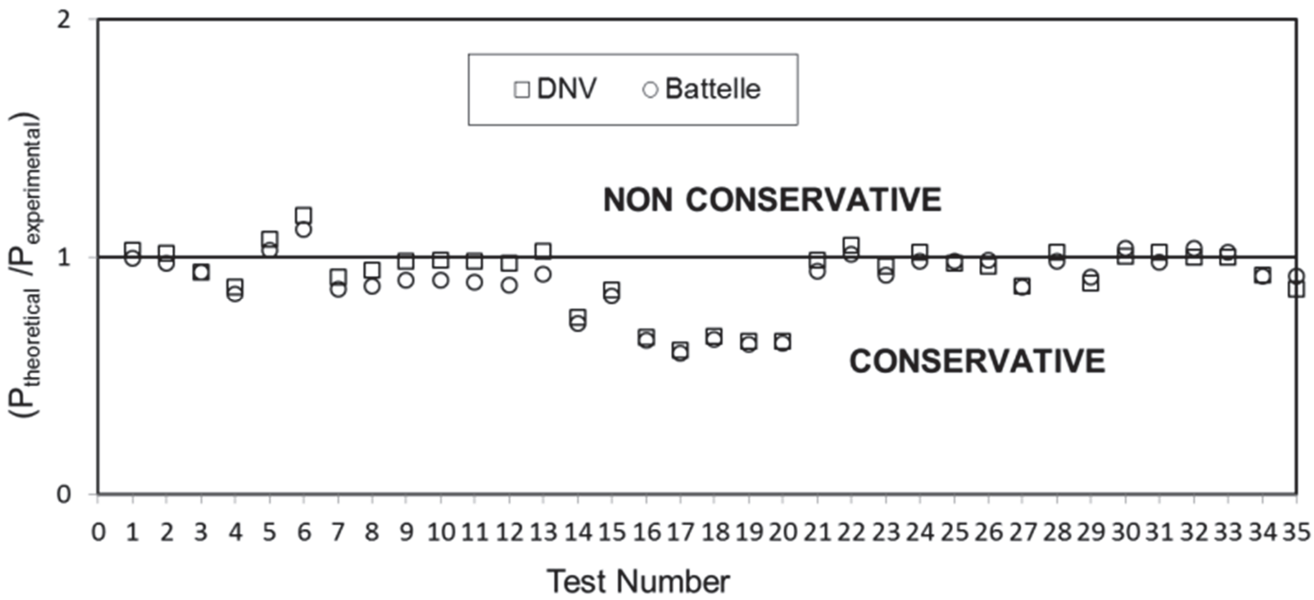

Figure 3: ($P_{theoretical}/P_{experimental}$) per test with accurate burst pressure using selected semi-empirical model.

The ASME B31G and Ritchie models give more conservative predictions of burst pressure in all 35 hydrostatic tests, however RSTRENG model gives mixed predictions some tests predictions are conservative and some are more non-conservative as shown in Fig.2. However,the DNV and Battele models give more accurate predictions which is closer to the experimental burst pressure except in some burst tests (Fig.3). The DNV and Battele models show good predictions, but the burst pressures are higher than the measured ones in a few experiments (test number 5 and 6) where the $\sigma_{flow} \geq \sigma_{ult}$ condition is met [19]. As already mentioned in the previous section, the material with close values of yield strength and ultimate strength violate the flow stress condition under these criteria, which leads to an over-predicted pressure. Thus, special attention should be given to the material properties before selection of the criterion for the prediction of the burst pressure in order to avoid over-prediction. Semi-empirical model selection should be based on the requirement of the level of accuracy and conservativeness for a particular area of application.

NEW METHODOLOGY FOR PREDICTION OF THE BURST PRESSURE

It is difficult to represent the actual corroded area in the analysis, as the natural corrosion process is non-uniform in nature, which leads to questionable prediction of the burst pressure of the pipe. A large variation of the remaining strength value with respect to the model has an impact on the final theoretical burst pressure, as it is difficult to represent the actual defect area. In this section the author proposed a methodology to evaluate the conservative burst pressure. This methodology is formulated with accounting for the minimum thickness (weakest section of the pipe) over the length of the pipe for evaluating the conservative burst pressure (Fig.4). This formulation can be used for any type (arbitrary) of defect shapes and sizes, as it does not depend on the defect area and requires only the pipe's geometry and elastic properties. Most conservative theoretical predictions of the burst pressure can be calculated considering the weakest section of the metallic pipeline which is normally the defect section.
Assuming, the weakest section thickness (e-d) as the pipe thickness and estimating the burst pressure in two cases: open-ended and closed-ended cylinder.

$$P^{th}_{max} = \frac{(t-d)*\sigma_{uts}}{r_i} \text{ open ended cylinder} \tag{5}$$

$$P^{th}_{max} = \frac{2*(t-d)*\sigma_{uts}}{\sqrt{3}*r_i} \text{ closed ended cylinder} \tag{6}$$

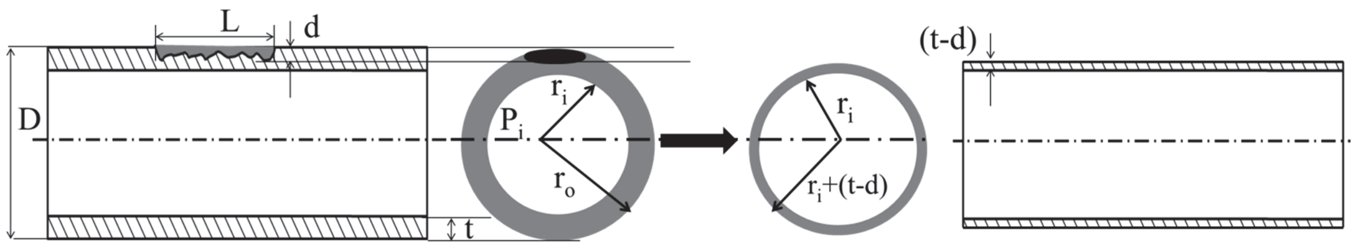

Figure 4: Metal loss in the pipe (a) Pipe geometry with defect (b) Pipe geometry with minimum thickness for new model

Fig. 5 shows the comparison between the predicted burst pressure and the experimental burst pressure. It is clearly observed that the experimental burst pressure (35 burst tests) is higher than the predicted burst pressure using the proposed methodology. This methodology can be implemented to any arbitrary corroded specimen and estimate the most conservative burst pressure, as it is considered the thinnest (weakest) section of the pipe for the calculation of the burst pressure. On the other hand, an accurate pressure can be obtained with the same methodology with accounting the axial stress which is realistic to the hydrostatic burst tests. Actual testing scenario and assumptions during the analysis, makes a difference in the predicted and experimental burst pressure. Fig. 6 shows the predicted burst pressure with accounting the axial stress which gives more accurate results compared to without accounting axial stress. The predicted pressure with accounting axial stress in the analysis is validating the concept for accurate results suggested by many researchers [35-37]. The predicted burst pressure is 1.15 times higher when axial stress is accounted in the analysis. Besides the axial stress, radial stress and elasto-plastic behavior far from defect can be accounted in the analysis for a more accurate prediction of the burst pressure. It is possible to extend the study to account radial stress and elasto-plastic behavior; however the resulting expression can be more complex and require additional material properties.

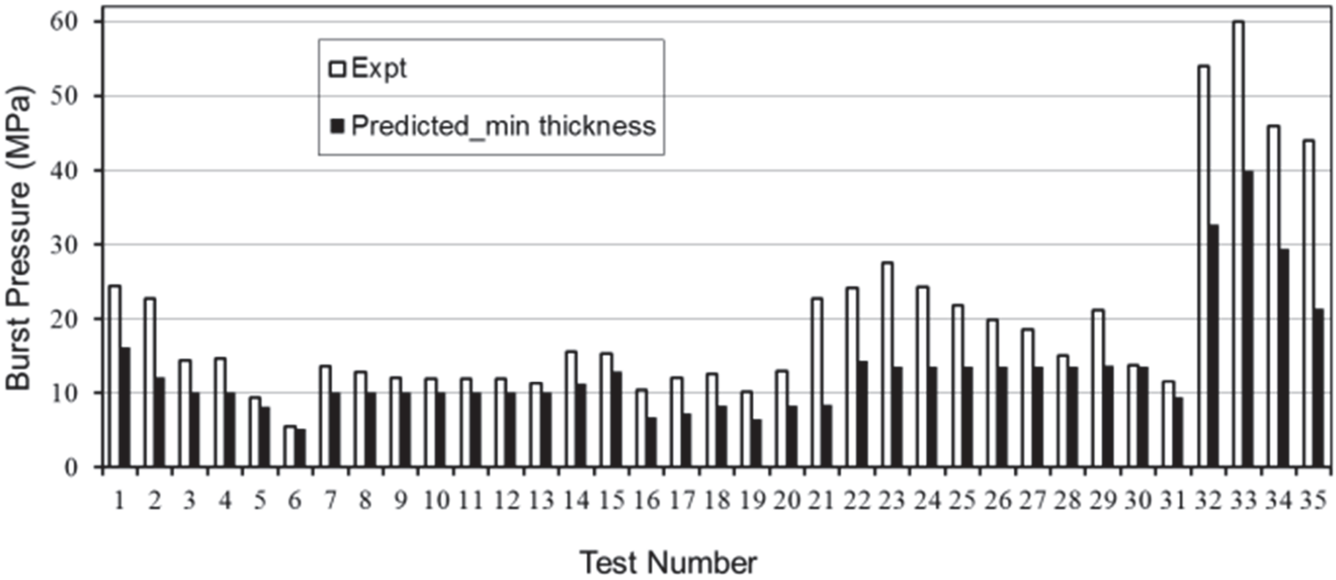

Figure 5: Comparison between predicted and experimental burst pressure using the proposed model

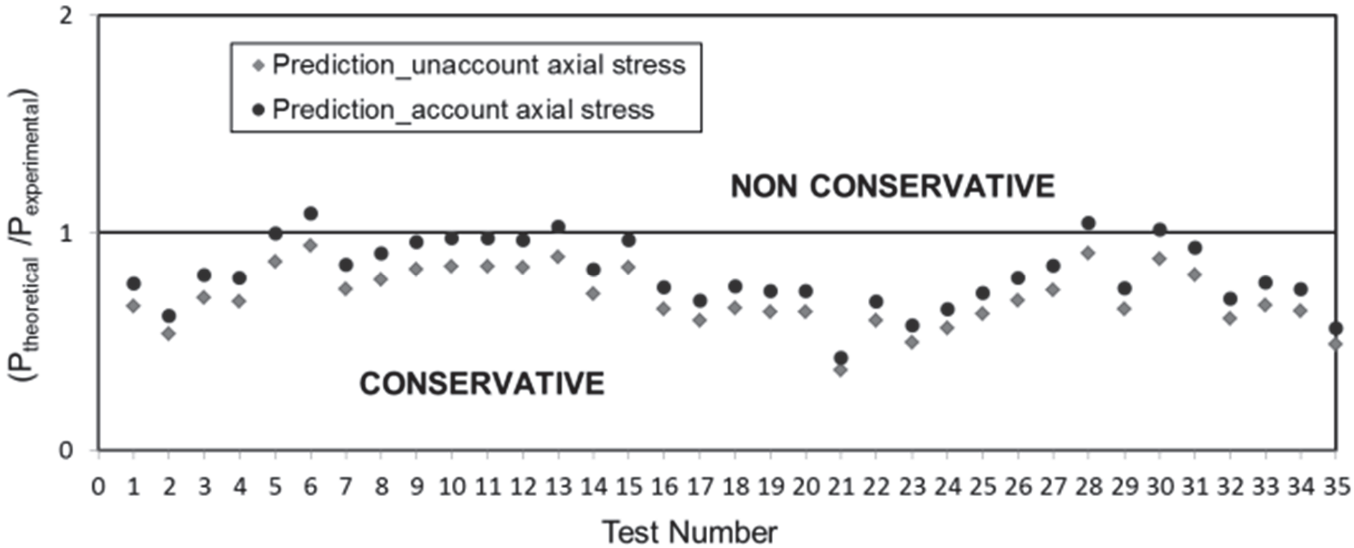

Figure 6: ($P_{theoretical}/P_{experimental}$) per test using proposed methodology with and without account axial stress

CONCLUSIONS

This study presents an assessment of the theoretical burst pressure of metallic pipelines with wall loss defects using different semi-empirical models and validated with the experimental results of 35 hydrostatic burst tests obtained in different laboratories.

There is quite a variation of burst pressure between the theoretical and experimental results with respect to the different semi-empirical models. Most of the models predict very conservative burst pressures with respect to the experimental burst pressure. The higher conservativeness is due to neglecting the axial stress and width of the defect section in the analytical model. A mixed prediction of the burst pressure (over predicted/ conservative/accurate) for different tests under the same model is due to the different corroded geometry, shape and material properties of the pipeline. The selection of the empirical model is an open question as it gives dispersed values of burst pressure, so it is needed to be

careful about pipe geometry and material properties of the pipe while selecting the model. Selection of criterion should be based on the requirement of the level of accuracy and/or conservativeness for a particular area of application.
The new methodology is applicable for any type of arbitrary defect in a pipeline considering the weakest section of a damaged pipeline predicts the most conservative burst pressure. This methodology can predict accurate burst pressure if the axial stress is accounted for in the analysis. The proposed methodology aims to provide a lower limit of theoretical burst pressure (conservative) for safe operation in a critical area of application.

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NOMENCLATURE

P_b	Burst pressure (MPa)
P_{max}^{th}	Maximum theoretical pressure (MPa)
n	Strain Hardening
r_i	Internal radius of pipe (mm)

r_o	External radius of pipe (mm)
t	Pipe thickness (mm)
σ_y	Yield stress of pipe (MPa)
σ_{ult}	Ultimate stress of pipe (MPa)
α_θ	Remaining strength factor
L	Defect length (mm)
w	Width of defect section (mm)
D	External diameter of pipe (mm)
d	Depth of defect (mm)
σ_{flow}	Flow stress of pipe (MPa)
k	Material constant
P_b^{th}	Theoretical burst pressure (MPa)
M_t, Q, A_f, M_t	Bulging factors