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Collapse prediction of pipe subjected to combined loads

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ABSTRACT

Prediction of tubular performance has over the last decades improved with models that are more accurate. There is a trend in the oil and gas industry where traditional uniaxial modelling is given less importance and the triaxial consideration is gaining ground. The American Petroleum Institute (API) added a formula to the standard to consider the effect of internal pressure on the collapse strength in the early 1980s. In 2015, API issued an addendum to the API Technical Report 5C3 (TR 5C3) where the triaxially based collapse strength method was incorporated. This was a more accurate method of incorporating the effect of internal pressure and axial stress on collapse strength. The validity of the formula was demonstrated by collapse strength tests with simultaneous internal pressure by an API work group – API WG 2370 (Greenip, 2016).

In 2007, API/ISO presented an ultimate strength (ULS) method for predicting collapse. The new calculation, referred to as the Klever & Tamano model, was developed by API/ISO Work Group 2b (WG2b) under the Steering Committee 5 (SC5) for tubular goods. Following 2986 collapse tests of quenched and tempered tubular specimens; the Klever & Tamano (K&T) model has since been presented as the most accurate ULS model for collapse prediction.

This paper compares the collapse prediction performed by the Klever & Tamano model with the 2015 API model using the triaxial collapse tests performed by Greenip for API. Comparison of the K&T (ULS) model and the traditional API (minimum performance) model requires some considerations to establish common ground before the results can be compared. The K&T model builds on a probabilistic estimation of the pipe properties while key components of the API prediction is empirical. The resulting collapse prediction for the entire batch is 3.11% lower than actual for K&T and 20.9% for API. Using two standard deviations, the collapse prediction of K&T is 14.7% lower than actual. Increasing to three standard deviations, the K&T model coincides with the API triaxial model from 2015 for the investigated pipe. No figures reported include any design factors. These results support that slimmer tubular designs can be made, exercising detailed control of safety margins to collapse. A generic example shows a reduction of $47,000USD per well for a typical 13 000 ft long well in an 8.6 lb/gal (1.03 sg) pressure gradient.

1. Introduction

The tests to verify the modification of the API formulas for collapse prediction to accommodate triaxial stress state were performed in 2013 by API WG 2370. 24 collapse tests were performed on a casing with 7” outer diameter, nominal weight of 26 lbs/ft, and grade L-80. The collapse tests were performed with either open or closed end conditions (OE/CE), which gives input to a triaxial state with internal pressure and no axial load, and a scenario of internal pressure and axial stress - respectively. The same test data have been applied to the Klever and Tamano model described in API/ISO TR 10400 (Brechan et al., 2018) and compared with the results presented by API WG 2370 (Greenip, 2016)[1].

The updates in the addendum to “ANSI/API Technical Report 5C3/ISO 10400:2007” issued in 2015 are all incorporated in the latest versions released in 2018. It comprises four equations, which predicts collapse depending on the ratio of outer diameter “D” to wall thickness “t” and material yield strength. These categories are displayed in Fig. 1, where each of the formulas are represented in a designated color. The categories are called yield strength, plastic, transition and elastic -collapse. Together, they form a so-called “minimum performance” prediction, i.e. very low probability for pipe failure due to collapse. The background and validity of the API collapse calculation is discussed in the subsequent chapter.

The Klever and Tamano model applied on the data set from the work of API WG 2370 is the one developed by API/ISO Work Group 2b (WG2b) under the Steering Committee 5 (SC5) for tubular goods first time presented in API/ISO TR 10400:2007 (Brechan et al., 2018). WG2b modified the original Klever and Tamano (K&T) model and found it to be the most accurate when comparing with 10 other collapse models. K&T is an ultimate limit strength model (ULS), which means that it predicts when pipes will fail. A more informed and accurate prediction of pipe collapse can slim down the casing program for many standard well designs and contribute to lowered cost and reduced environmental footprint since producing 1 ton of steel is equivalent to the approximate same amount of CO_2.

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[1] For designs limited by collapse. The saving is in the same range for designs limited by burst (Brechan, 2019).

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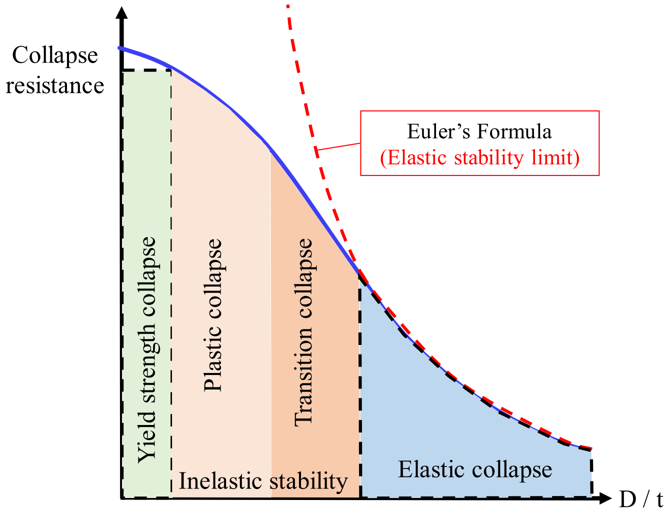

Fig. 1. API categories of tubular collapse.

2. Collapse prediction

Comparing the results from a minimum performance model (API) with an ULS model (K&T) has some inherent challenges. The minimum performance model has some safety factors built in while there is no such element in an ULS model. There are several ways to find "common ground" for these models, where the two obvious methods would be to eliminate the embedded safety factor in the minimum performance method or to add a safety factor to the ULS model. The latter is the chosen way in this paper for the following reasons:

- The API collapse model is not consistent over the four categories for collapse prediction seen in Fig. 1 – the extreme categories were derived mathematically and the two in the center are derived empirically. Fig. 2 displays the gap between real performance of pipe and the API collapse prediction model over the four categories as presented in Fig. 1.
- There are three material parameters as input for the API model (D, t and yield), where the nominal values should be used.
- A probabilistic risk-based approach to failure is gaining traction in the industry. The ULS model was developed using statistics to determine probability of failure from multiple material parameters.

Adjusting the parameter input for the ULS model at different confidence levels and then comparing to the API model using the real collapse data can provide an understanding of the embedded safety factor in the API model and accuracy of both models.

Suppliers are capable of controlling dimensional and mechanical properties of tubulars in the manufacturing process today. Important dimensional properties such as external diameter to wall thickness ratio, ovality and eccentricity are central for collapse resistance. In addition, the mechanical properties influencing collapse such as residual stresses, heat treatment processes for yield strength are controlled to ensure the minimum collapse performance as shown Fig. 2, which is from one of the largest manufacturers of Oil Country Tubular Goods (OCTG).

2.1. API collapse

Modelling collapse according to the API calculation entails a few important steps, which can be summed up to:

a) The D/t ratio and yield stress calculation identifies which of the four collapse equations is relevant for the specific pipe
b) If the D/t and yield calculation is close to the limit between two collapse categories, both should be calculated and the one with the lowest prediction should be used
c) The calculated value should be understood as "uniaxial", i.e. valid only where pipe has no axial stress[2]
d) For pipe with internal pressure, axial stress or both, a pre-calculation is required before the collapse limit is determined, see Eq. (1). This equation was one of the updates in the ISO 10400:2007 addendum issued in 2015. Its role is to modify the yield strength to accommodate the triaxial effects from internal pressure and axial stress on the collapse strength of the tubular investigated.

$$\sigma_{ys,\ e} = \sigma_{ys}\left[\sqrt{1-\frac{3}{4}\left(\frac{\sigma_a+p_i}{\sigma_{ys}}\right)^2}-\frac{1}{2}\left(\frac{\sigma_a+p_i}{\sigma_{ys}}\right)\right] \tag{1}$$

where:
σ_{ys} is the specified minimum yield strength
σ_a is the component of axial stress not due to bending
p_i is the internal pressure
$\sigma_{ys,e}$ is the combined loading equivalent grade, the equivalent yield strength

2.1.1. Interpretation of modelled results

The API collapse formulas were presented in their current form at the API Standardization Conference and reported in API Circular PS- 1360 dated September 1968. Fig. 3 is an overview of different pipe sizes in grade C-75 which illustrate the different API collapse categories.

For grades with higher yield, the limits between the regimes would descend to a lower D/t value, and vice versa.

2.1.1.1. Yield strength collapse. Yield strength collapse typically takes place for pipes with small diameter, large wall thickness, and high yield strength. Deformation due to exceeding the yield strength can relate to the material specific behavior often seen in tensile or compressive tests. The formula used for determination of yield strength collapse was derived from the theoretical von Mises maximum distortion energy theory for yielding. This means that pipe failing due to yield will be limited to the von Mises ellipsis marked with red in Fig. 4.

2.1.1.2. Elastic collapse. Elastic collapse follows a failure mechanism, which is predominantly governed by instability similar to what is seen with Euler columns. The formulas presented by API for prediction of yield strength collapse and elastic collapse were both derived from theory. As seen from Fig. 3, pipe failing according to elastic collapse would typically be large diameter and be made in low yield material. Since elastic collapse is not affected by axial stress, these pipes would be limited to the horizontal line crossing point marked "2" in Fig. 4. This includes the light blue-stapled line, which is for elastic collapse only.

2.1.1.3. Inelastic collapse – plastic and transition collapse. In material science, the area between yield strength and elastic collapse is one entity. However, API adds a theoretical area for "transition collapse". The formulas used to derive collapse for pipe in this area are empirical. In the 1960s, the plastic collapse formula was developed from 2488 collapse tests performed on pipe in grades K55, N80 and P110, see Fig. 5. The tests were performed with no axial stress, which means they are uniaxial, c.f. point "2" in Fig. 4. The collapse limit is curved in the fourth quadrant – see the blue line between points marked "2" and "3" in Fig. 4. This reduction from the uniaxial value was previously governed by Eq. (2), which was limited to tension only. I.e. quadrant four in Fig. 4. Transition collapse was developed to fit the minimum performance of

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[2] Exception is for « Elastic collapse » which is not influenced by axial stress.

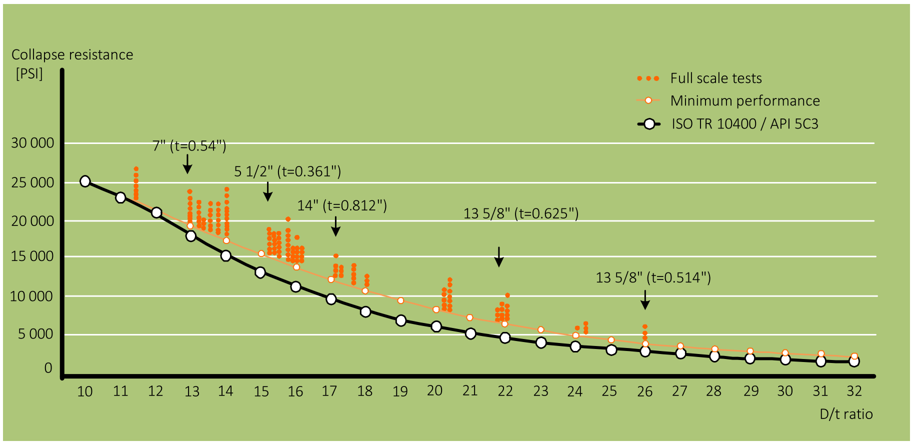

Fig. 2. Collapse resistance of tubulars as per suppliers manufactured properties.

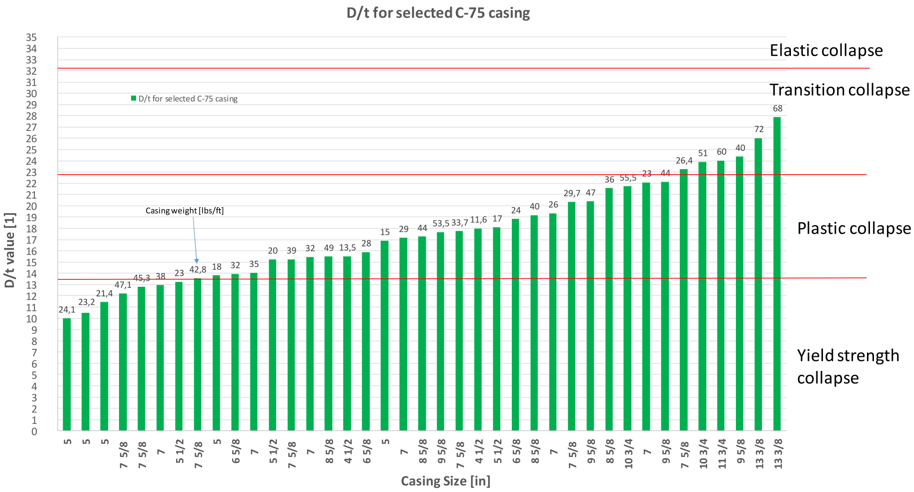

Fig. 3. Collapse regimes for C-75 pipe.

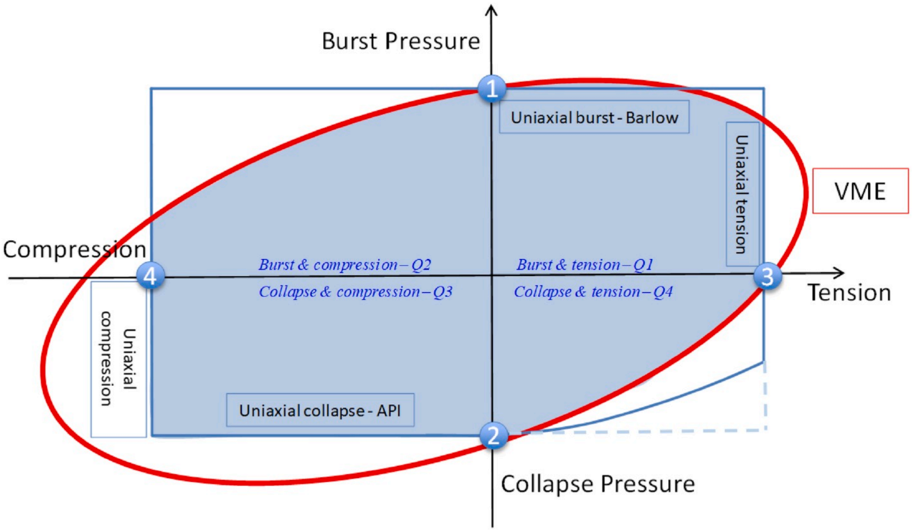

Fig. 4. Triaxial failure criterion.

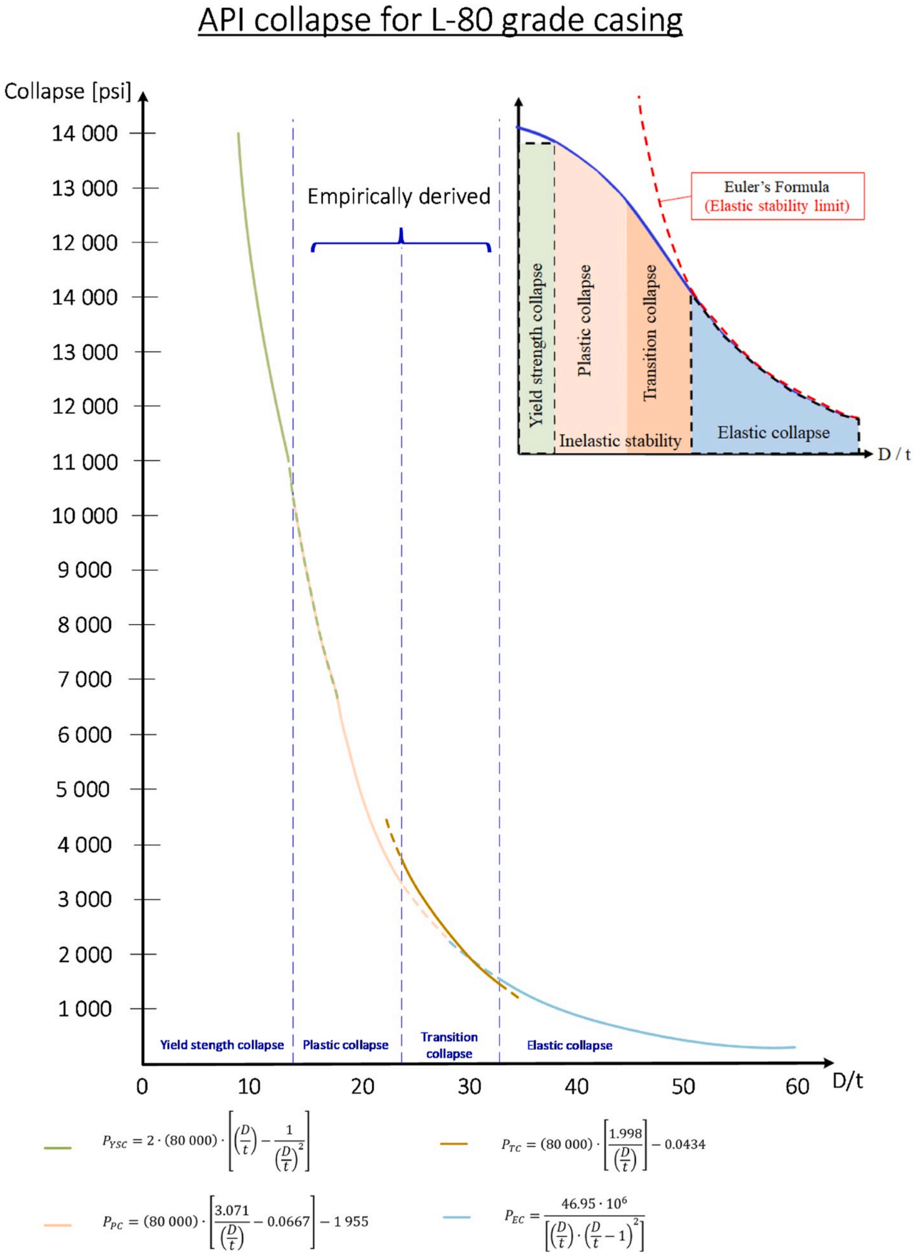

Fig. 5. Empirical derivation of API Plastic collapse and Transition collapse with Euler's elastic collapse for columns inserted.

pipe collapse, see Fig. 5.

$$\sigma_{ys,\ e} = \sigma_{ys}\left[\sqrt{1 - \frac{3}{4}\left(\frac{\sigma_a}{\sigma_{ys}}\right)^2} - \frac{1}{2}\left(\frac{\sigma_a}{\sigma_{ys}}\right)\right] \tag{2}$$

The change from Eq. (2) to Eq. (1) as published in the 2015 addendum of API/ISO TR 10400:2007 resulted in three significant changes:

1) The effect of internal pressure on collapse resistance of pipe could be considered through manipulation of the yield strength.[3] As described by Greenip, Eq. (1) presumes equal influence on yield strength reduction from internal pressure and axial stress (Greenip, 2016).
2) The reduced yield strength is applied to the traditional formulas for collapse prediction and $P_{collapse}$ is replaced with ($P_{collapse}$ - $P_{internal}$).
3) Triaxial collapse prediction is expanded to include compression,[4] i.e. the third quadrant in Fig. 4.

In (Greenip, 2016), the difference in collapse prediction for Eq. (2) and Eq. (1) for 13 3/8″ 72 lbf/ft N-80 pipe is plotted. This pipe has a D/t ratio of 26, which would place it in the segment of "transition collapse". An important note to bullet point 2 above is the potential change from transition collapse to elastic collapse when the yield strength is reduced

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[3] Earlier accommodation of effect from internal pressure on collapse resistance was handled through equation (43) in API/ISO TR 10400:2007. This formula considers the difference in area between inside and outside the pipe. The 2015 API/ISO amendment and SPE-178806 (Greenip, 2016) have further background for the change.

[4] Before the 2015 addendum, there would be collapse prediction for triaxial stress states in quadrant 3 for yield strength and elastic collapse only. The industry practice was to extend the uniaxial collapse prediction as shown by the horizontal line to the left of point marked "2" in Fig. 4.

to about half (~42,350 lbs).

2.2. Klever & Tamano collapse

The theory in the software model originates from Tamano et al. (Tamano, 1983) which was later developed with Klever (2006). It was modified by the API/ISO work group following a series of collapse tests of quenched and tempered (Q&T) pipe (1139 API + 1847 high compression) and 185 tests of non-Q&T pipe. First presented in API 5C3/ISO TR 10400:2007, the modified Klever & Tamano (K&T) has since been presented as the most accurate model for prediction of collapse in both standards.

The modified K&T predicts the exact collapse performance of pipe and is therefore a ULS model. The theory begins with collapse of a "perfect" pipe and then accommodates manufacturing imperfections. Collapse depends on yield stress, average outside diameter, average wall thickness, eccentricity, ovality, and residual stress of the pipe. These properties were mapped from pipe supplied by the many manufacturers participating in the work of the API/ISO WG2b. The measured properties were subjected to statistical analysis which enable probabilistic collapse performance. Each parameter has a probability density function (PDF) which are listed in the standards and displayed in Table 1.

The K&T collapse model was the built considering triaxial stress states, presenting the collapse resistance with no further calculation required. However, selecting the right PDF input is important.

From Table 1, it is stated that collapse performance of pipe often is a distribution as shown by the blue-stapled line in Fig. 6. When making tubular design, there is often a margin between the lowest expected pipe performance and the highest expected load, see Fig. 6.

The gap shown as "hidden safety margin" in Fig. 6, can also be seen in Fig. 2 between the minimum performance according to the supplier and API collapse performance.

The modified K&T calculation has a "decrement function" as described by Eq (3).

$$H_t = 0.127ov + 0.0039ec - 0.440\left(rs / \sigma_y\right) + h_n \qquad 3)$$

where:

H_t is the decrement function
ov is ovality [%]
ec is eccentricity [%]
r_s is residual stress [Psi]
σ_y is yield stress [Psi]
h_n is a factor related to the (typical rounded) tensile test curve of low yield steel qualities

The decrement function describes the impact of the pipes' physical properties related to collapse resistance. To get a representative value and a realistic pipe performance, statistical values in the distribution of each of the input parameters are used derive the probability distribution of collapse resistance as shown in Fig. 7. The K&T software model developed and a broader background of the theory of K&T collapse prediction is presented in another paper (Brechan et al., 2018).

Table 1
Probability distribution and data representativeness for each input parameter.

Parameter	Data representativeness	Probability distribution
Yield strength	Grade, heat treatment, and rotary straightening type	Gaussian
Ovality	Forming process	Two-parameter Weibull
Eccentricity	Forming process	Two-parameter Weibull
Residual stress	Rotary straightening type	Gaussian
Outer diameter	Forming process	Gaussian
Wall thickness	Forming process	Gaussian
Collapse pressure	Product	Gaussian

2.2.1. Pipe specific properties

Using the specific properties of the pipe will give "exact" collapse performance, i.e. not minimum performance. A single prediction using the specific pipe properties would be accurate for the pipe under investigation. Considering the possibility that a batch of pipe may have a variety of values for each of the listed parameters in Table 1, a probability-based input of these parameters would produce a more representative collapse resistance.

2.2.2. Suppliers' batch specific parameters: ensemble PDF

WG2b collected a considerable amount of manufacturing statistics of the parameters listed in Table 1. Measurements of outer diameter, wall thickness and 6000 samples of ovality and eccentricity. Residual stress measurements are reported for 470 hot rotary straightened (HRS) samples and 943 cold rotary straightened (CRS) samples. 1374 tensile tests of P-110 grade casings were performed to map yield strength distribution.

With a good mapping of the input parameters, the pipe stress tolerance distribution as shown in Figs. 6 and 7 can be produced. The probability of failure from collapse can be set at any desired level, e.g. 2 standard deviations would mean that 97,5% of the manufactured pipe would have a higher tolerance. Adding that the design factor between highest load and lowest collapse performance often is 1.1, which provides an adequate risk level for many operators[5]

3. Test data and results

An overview of the tests performed by Stress Engineering Services Inc for API is listed in Table 2. The collapse tests were performed on 7" 26 ppf L-80 pipe. Test set number 4 and 5 includes axial stress and are therefore of special interest.

Open End Samples:

- Length: 8 × outer pipe diameter = 56"
- Tests performed according to latest revision of API 5CT and ISO 10400 in 2013.
- No axial stress

Closed End Samples:

- Length: 10 × outer pipe diameter = 70"
- Tests not in compliance with API/ISO 10400.
- Axial stress induced from capped ends

Further details related to the tests are presented by Greenip (2016).

3.1. Methodology

The application implements the set of equations presented in the paper by Klever and Tamano (Klever, 2006) using the version labeled eq. (26) in the original paper. The axial force is a result of the pressure differential across the casing wall due to the experimental setup. A root-finding routine has been used solve the system of equations. Table 3 displays the input parameters of the model. Experimental data and associated equipment data are listed in (Greenip, 2016). The parameter for wall thickness is chosen on recommendation from the authors of (Brechan et al., 2018) based on results from finite element analysis. Poisson's ratio and the elastic modulus is specified by the casing

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[5] 2 standard deviations is often used with anti-collision applications in directional drilling.

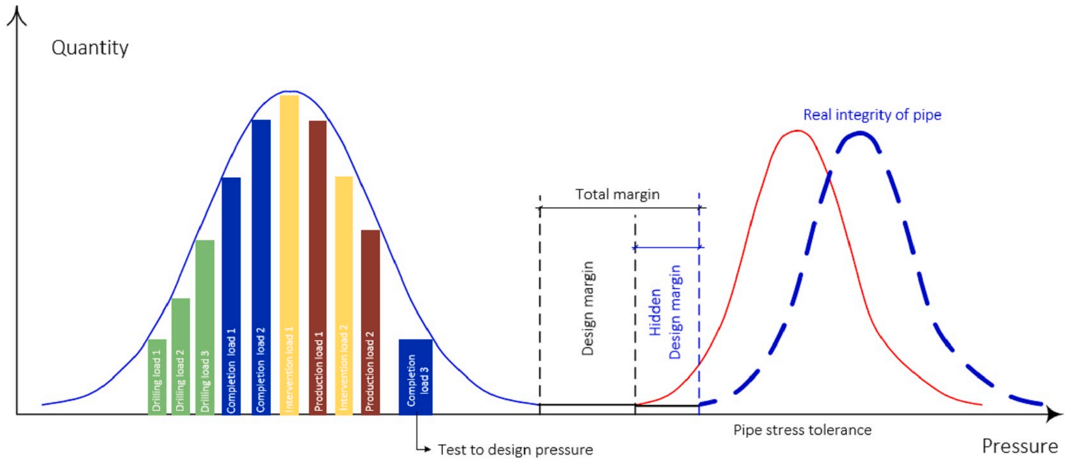

Fig. 6. Miscellaneous loads, margin to pipe performance and pipe performance distribution.

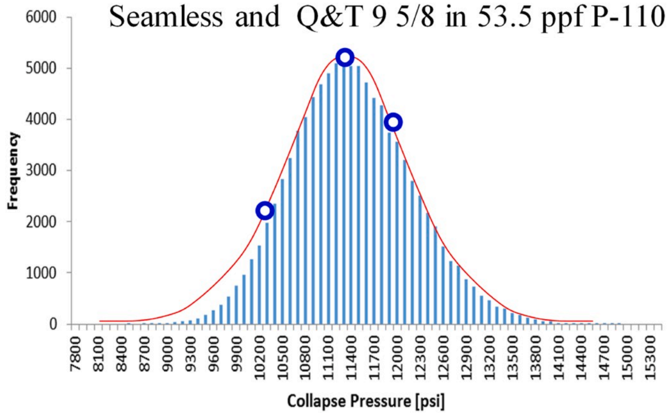

Fig. 7. Collapse prediction of 9 5/8″ 53.5 ppf P-110 casing with 100,000 iterations of parameter input as listed in Table 1 (result in blue columns). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Collapse test data from API WG 2370.

Open/ closed -end		Internal pressure [psi]	Collapse [psi]: specimen 1 through 5	Mean [psi]	St-dev
1	OE	0	7339, 7419, 7023, 7218 and 7631	7326	226.6
2	OE	5000	7352, 7588, 7178, 7222 and 7361	7340	159.9
3	OE	7500	7372, 7619, 7004, 7130 and 7418	7313	249.9
4	CE	0	7221, 7388, 7286, 7608 and 7641	7429	188.7
5	CE	5000	-NA-, 7445, 7680 7398 and 7460	7496	125.6

material. The model bias factors originate from the ISO standard (ISO/API-10400:2007), where values for hot rotary straightened L-80 casing are used. As most Q&T-tubulars feature a sharp-knee stress strain curve, no correction is needed and the shape constant is set to zero (ISO/API-10400:2007). The parameters defining the probability distributions for the remaining input listed in Table 3 originates from ensemble PDFs for HRS casing provided in (ISO/API-10400:2007). A detailed description and explanation of the values in Table 3 can be found in (Brechan et al., 2018).

Table 3
Parameters in K&T model.

INPUT				
Variable	Explanation	Distribution	Value	
c	Parameter for wall thickness	Constant	6.00	
v	Poisson’s ratio	Constant	0.28	
h_n	Shape of the stress strain curve	Constant	0	
k_e	Model bias factor	Constant	0.825	
E	Elastic modulus	Constant	2.068*10^11 N/m^2	
k_y	Model bias factor	Varying	0.865	
rs	Residual stress	Gaussian	Mean (μ) Standard deviation (σ)	−0.138 0.06997
σ_y	Yield strength (L80)	Gaussian	Mean (μ) Standard deviation (σ)	1.10 0.04642
t	Wall thickness	Gaussian	Mean (μ) Standard deviation (σ)	1.0069 0.02608
D	Outer diameter	Gaussian	Mean (μ) Standard deviation (σ)	1.0059 0.00182
ov	Ovality	2-parameter Weibull	Scale para. (λ) Shape para. (κ)	0.236 1.53
ec	Eccentricity	2-parameter Weibull	Scale para. (λ) Shape para. (κ)	4.42 1.60

By application of random number generation, a Monte Carlo analysis has been run using the constants and probability distributions listed. The model selects a random value from every probability distribution and solves the equation with the relevant input parameters. This process is repeated a number of times to create a probability distribution for the output parameter. Note that the “external pressure equivalent” discussed in (Klever, 2004), is not applied in this analysis.

4. Results

Fig. 8 shows the results of the analysis where recorded actual collapse is plotted and compared to the mean value and two standard deviations of the probability distribution of the collapse pressure. The test number on the x-axis corresponds to the order listed in Table 2, meaning that the first 15 test are open-ended (OE) and the last nine are close-ended (CE). Using probability distributions for the relevant input parameters and the methodology outlined in API addendum 2015, the mean value of the API standard prediction is shown in the same figure. Table 4 displays the relative difference between simulated and

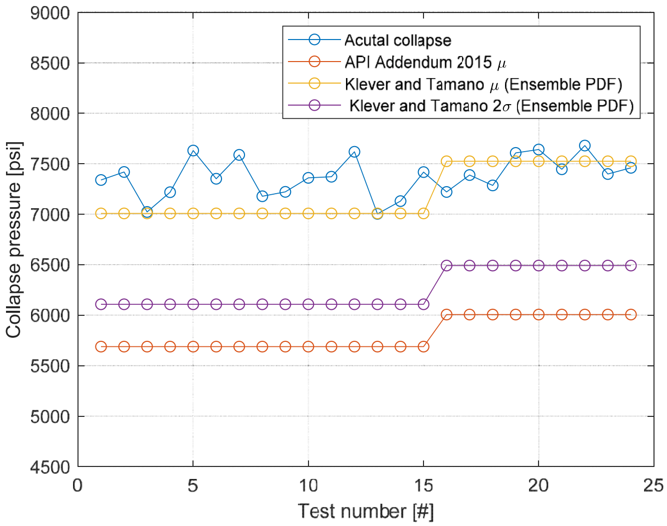

Fig. 8. Simulated collapse pressure for test samples and recorded collapse pressure failure.

Table 4
Relative difference between simulated and experimental values.

Test	K&T	API	Comment
OE	4.27%	22.3%	Mean of predictions (μ) zero axial stress
CE	1.96%	19.4%	Mean of predictions (μ) with axial stress
OE	16.5%	–	2 standard deviations (2σ) zero axial stress
CE	12.9%	–	2 standard deviations (2σ) with axial stress

experimental values split into open ended and closed ended categories. The results from the API model is approximately equivalent to 3.0 standard deviations from the mean using the K&T model.

5. Discussion

API developed the industry standard collapse prediction model more than 50 years ago. Most frequently used pipes are in plastic and transition collapse categories, which for some pipes have a hidden safety factor ranging between 10 and 35% as shown in Fig. 2. The plot in the figure is for zero axial stress. The analyzed specimens are seamless with hot rotary straightening, which has a different performance from cold rotary straightening. The K&T model is specific for each material parameter and manufacturing process. The K&T calculation method is the most accurate ULS, i.e. predicts the actual collapse of each pipe quality. Knowing the basic material properties, it is possible to design the safety factors carefully towards the loads the pipes will be exposed to. An example of managing the safety factors could be to accept lower margin for initial pressure testing of a well in a field developed by depletion. The pipes are new, and the design pressure of the well will only reduce. More explicit, using the pipe quality examined in this paper, this pipe would not be approved for 5000 psi service using tubular design recommendations in standards. The API collapse listing for zero axial stress is 5410 Psi. Recommended design factor for collapse 1.1, i.e. max pressure with little axial stress involved is 4918 Psi. K&T provides information about the actual collapse of this specific pipe quality, i.e. 7000 to 7500 psi see Fig. 8. Should the pipe be part of a production liner, it will have low axial stress and the real safety factor for 5000 psi would be 1.4 with K&T prediction (~7000 Psi).

In other risk-based calculations such as anti-collision, i.e. risk for drilling into another well or missing the reservoir target, Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) propose a safety level of two standard deviations. In the case of the 5 first of the 25 tests investigated, the average difference between the investigated models is 2 standard deviations for K&T predicts 16.6% reduction in collapse, i.e. 6109 Psi. API predicts 5689 Psi which is a 22.3% reduction. The K&T coincides with the API model at 3 standard deviations.

Estimation of the impact of other pipes can be extrapolated from Fig. 2, where the range for inelastic collapse has an embedded design margin of 15%–35%. Using the triaxial calculations for collapse is provided by K&T or API in the API addendum from 2015 is essential to understand pipes performance in service. Because of the minimum performance approach, the API collapse prediction does not discriminate between manufacturing method or material properties of the pipe. It can therefore be concluded that the difference between the collapse prediction of K&T and API will vary proportionally with D/t range and manufactured quality as the gap between API calculation and real minimum performance of pipe shown by a large pipe manufacturer in Fig. 2. Therefore, ISO10400/API 5C3 states that K&T is more accurate (see section F.2.3.1 in the standards): the method is more precise over the range of D/t as displayed in Fig. 2.

One important note discussed in SPE-178806, the API approach of manipulating the yield strength to calculate triaxial collapse may have weaknesses for elastic collapse especially (Greenip, 2016). As discussed for Fig. 1, failure due to collapse becomes gradually less dependent on yield strength and more dependent on geometry with increasing D/t ratio.

6. Summary and conclusions

- Working with a minimum performance model and an ultimate state model requires some adjustments to arrive at "common ground" and enable comparable results.
- The API model does not consider the manufacturing method in collapse prediction and considers only the poorest performer as tested in the 1960s, leaving a hidden design margin for many manufactured pipes today.
- The K&T model gives good collapse prediction in the combined stress states investigated
- The safety factor of the prediction using the API model is equivalent to 3.0 standard deviations using the Klever and Tamano model with ensemble PDFs.
- There are potential for significant environmental and cost savings by careful analysis of the true safety margins in well designs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

B. Brechan: Conceptualization, Methodology, Validation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision. **A. Teigland:** Methodology, Validation, Resources, Data curation, Writing - original draft. **S. Dale:** Writing - review & editing, Visualization, Supervision, Project administration. **S. Sangesland:** Writing - review & editing, Visualization, Supervision, Project administration. **E. Kornberg:** Methodology, Resources, Data curation.

Appendix A. Cost saving example

Table 5 represents a small example limited to two casing strings.

Table 5
Simplified cost saving example.

Size [in]	Length [ft]	Original weight [lbs/ft]	New weight [lbs/ft]	Reduction [lbs]	$ saved [USD]
13 3/8	7000	72	61	77,000	$28,431
9 5/8	13,000	58.4	54.4	52,000	$19,200
					$47,630
		0.37 $/lbs[a]			

The displayed number may be a small cost for an offshore operation. But for a land well, saving this amount with no added consequence can be something to consider. Following the cost saving of the example above is a reduced carbon emission in excess of 45 metric tons.

Note1: The same saving can be made should the well design be burst limited (Brechan et al., 2019).

Note 2: The saving in this example is made from a generic well design with 8.6 lb/gal (1.03 sg) pressure gradient.

[a] Price of raw steel independent of manufacturing costs. Source: https://worldsteelprices.com/(April 2018).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petrol.2020.107158.

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