TECHNICAL REPORT

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Petroleum and natural gas industries — Formulae and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing

Industries du pétrole et du gaz naturel — Formules et calculs relatifs aux propriétés des tubes de cuvelage, des tubes de production, des tiges de forage et des tubes de conduites utilisés comme tubes de cuvelage et tubes de production

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 5, *Casing, tubing and drill pipe*.

This second edition cancels and replaces the first edition (ISO/TR 10400:2007), which has been technically revised.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Performance design of tubulars for the petroleum and natural gas industries, whether it is formulated by deterministic or probabilistic calculations, compares anticipated loads to which the tubular can be subjected to the anticipated resistance of the tubular to each load. Either or both of the load and resistance can be modified by a design factor.

Both deterministic and probabilistic approaches to performance properties are addressed in this document. The deterministic approach uses specific geometric and material property values to calculate a single performance property value. The probabilistic method treats the same variables as random and thus arrives at a statistical distribution of a performance property. A performance distribution in combination with a defined lower percentile determines the final design formula.

Both the well design process itself and the definition of anticipated loads are currently outside the scope of standardization for the petroleum and natural gas industries. Neither of these aspects is addressed in this document. Rather, it serves to identify useful formulae for obtaining the resistance of a tubular to specified loads, independent of their origin. It provides limit state formulae (see annexes) which are useful for determining the resistance of an individual sample whose geometric and material properties are given, and design formulae which are useful for well design based on conservative geometric and material parameters.

Whenever possible, decisions on specific constants to use in a design formula are left to the discretion of the reader.

Petroleum and natural gas industries — Formulae and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing

1 Scope

This document illustrates the formulae and templates necessary to calculate the various pipe properties given in International Standards, including

— pipe performance properties, such as axial strength, internal pressure resistance and collapse resistance,

— minimum physical properties,

— product assembly force (torque),

— product test pressures,

— critical product dimensions related to testing criteria,

— critical dimensions of testing equipment, and

— critical dimensions of test samples.

For formulae related to performance properties, extensive background information is also provided regarding their development and use.

Formulae presented here are intended for use with pipe manufactured in accordance with ISO 11960 or API 5CT, ISO 11961 or API 5D, and ISO 3183 or API 5L, as applicable. These formulae and templates can be extended to other pipe with due caution. Pipe cold-worked during production is included in the scope of this document (e.g. cold rotary straightened pipe). Pipe modified by cold working after production, such as expandable tubulars and coiled tubing, is beyond the scope of this document.

Application of performance property formulae in this document to line pipe and other pipe is restricted to their use as casing/tubing in a well or laboratory test, and requires due caution to match the heat-treat process, straightening process, yield strength, etc., with the closest appropriate casing/tubing product. Similar caution is exercised when using the performance formulae for drill pipe.

This document and the formulae contained herein relate the input pipe manufacturing parameters in ISO 11960 or API 5CT, ISO 11961 or API 5D, and ISO 3183 or API 5L to expected pipe performance. The design formulae in this document are not to be understood as a manufacturing warranty. Manufacturers are typically licensed to produce tubular products in accordance with manufacturing specifications which control the dimensions and physical properties of their product. Design formulae, on the other hand, are a reference point for users to characterize tubular performance and begin their own well design or research of pipe input properties.

This document is not a design code. It only provides formulae and templates for calculating the properties of tubulars intended for use in downhole applications. This document does not provide any guidance about loads that can be encountered by tubulars or about safety margins needed for acceptable design. Users are responsible for defining appropriate design loads and selecting adequate safety factors to develop safe and efficient designs. The design loads and safety factors will likely be selected based on historical practice, local regulatory requirements, and specific well conditions.

All formulae and listed values for performance properties in this document assume a benign environment and material properties conforming to ISO 11960 or API 5CT, ISO 11961 or API 5D and

ISO 3183 or API 5L. Other environments can require additional analyses, such as that outlined in Annex D.

Pipe performance properties under dynamic loads and pipe connection sealing resistance are excluded from the scope of this document.

Throughout this document tensile stresses are positive.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
Cauchy stress
true stress
force applied to the surface of a body divided by the current area of that surface

3.2
coefficient of variance
dimensionless measure of the dispersion of a random variable, calculated by dividing the standard deviation by the mean

3.3
design formula
formula which, based on production measurements or specifications, provides a performance property useful in design calculations

Note 1 to entry: A design formula can be defined by applying reasonable extremes to the variables in a limit state formula to arrive at a conservative value of expected performance. When statistically derived, the design formula corresponds to a defined lower percentile of the resistance probability distribution curve.

3.4
deterministic
approach which assumes all variables controlling a performance property are known with certainty

Note 1 to entry: Pipe performance properties generally depend on one or more controlling parameters. A deterministic formula uses specific geometric and material property values to calculate a single performance property value. For design formulations, this value is the expected minimum.

3.5
ductile rupture
failure of a tube due to internal pressure and/or axial force in the plastic deformation range

3.6
e
Euler's constant
2,718 281 828

3.7
effective axial force
material axial force (pipe wall axial stress times cross-sectional area) adjusted for the effect of internal and external pressure

Note 1 to entry: When a tubular is bent laterally into a circular arc, the pressures apply a lateral uniform distributed load (UDL) of $(p_i A_i - p_o A_o)/R$. For small deflections, the curvature is defined as $1/R \cong d^2y/dx^2$, thus, this term can be grouped with the tension term $F\, d^2y/dx^2$ in the governing differential formula. For bending and buckling, the tubular therefore acts as if it were loaded by the *effective axial force* $F_{eff} = F_a - p_i A_i + p_o A_o$[141]. It should be seen as a convenient grouping of terms, which determines the structural response: it does not exist as a physical axial force.

3.8
engineering strain
dimensionless measure of the stretch of a deforming line element, defined as the change in length of the line element divided by its original length

3.9
engineering stress
force applied to the surface of a body divided by the original area of that surface

3.10
fracture pressure
internal pressure at which a tube fails due to propagation of an imperfection

3.11
inspection threshold
maximum size of a crack-like imperfection which is defined to be acceptable by the inspection system

3.12
J-integral
measure of the intensity of the stress-strain field near the tip of a crack

3.13
label 1
dimensionless designation for the size or specified outside diameter that may be used when ordering pipe

3.14
label 2
dimensionless designation for the mass per unit length or wall thickness that may be used when ordering pipe

3.15
limit state formula
formula which, when used with the measured geometry and material properties of a sample, produces an estimate of the failure value of that sample

Note 1 to entry: A limit state formula describes the performance of an individual sample as closely as possible, without regard for the tolerances to which the sample was built.

3.16
logarithmic strain
dimensionless measure of the stretch of a deforming line element, defined as the natural logarithm of the ratio of the current length of the line element to its original length

Note 1 to entry: Alternatively, the logarithmic strain can be estimated as the natural logarithm of one plus the engineering strain.

3.17
mass
label used to represent wall thickness of tube cross section for a given pipe size

3.18
pipe body yield
stress state necessary to initiate yield at any location in the pipe body

3.19
principal stress
stress on a principal plane for which the shear stress is zero

Note 1 to entry: For any general state of stress at any point, there exist three mutually perpendicular planes at that point on which shearing stresses are zero. The remaining normal stress components on these three planes are principal stresses. The largest of these three stresses is called the maximum principal stress.

3.20
probabilistic method
approach which uses distributions of geometric and material property values to calculate a distribution of performance property values

3.21
synthesis method
probability approach which addresses the uncertainty and likely values of pipe performance properties by using distributions of geometric and material property values

Note 1 to entry: These distributions are combined with a limit state formula to determine the statistical distribution of a performance property. The performance distribution in combination with a defined lower percentile determines the final design formula.

3.22
template
procedural guide consisting of formulae, test methods and measurements for establishing design performance properties

3.23
TPI
threads per inch

Note 1 to entry: 1 thread per inch = 0,039 4 threads per millimetre; 1 thread per millimetre = 25,4 threads per inch.

3.24
true stress-strain curve
plot of Cauchy stress (ordinate) versus logarithmic strain (abscissa)

3.25
yield
permanent, inelastic deformation

3.26
yield stress bias
ratio of actual yield stress to specified minimum yield stress

4 Symbols

A hand-tight standoff, turns

A_c empirical constant in historical API collapse formula

A_{crit} area of the weaker connection component at the critical cross section

A_{gbtj} critical dimension on guided bend test jig, denoted as dimension A in ISO 3183 or API 5L

A_i area to pipe inside diameter; $A_i = \pi d^2/4$

A_{jc} area of the coupling cross section; $A_{jc} = \pi/4\ (W^2 - d_1^2)$

A_{jp} area of the pipe cross section under the last perfect thread

A_o area to pipe outside diameter; $A_o = \pi D^2/4$

A_p area of the pipe cross section; $A_p = A_o - A_i$

$A_{p\ ave}$ average area of the pipe cross section; $A_p\ \text{ave} = \pi/4\ [D_{ave}^2 - (D_{av}\text{e} - 2\ t_{c\ ave})^2]$

A_s cross-sectional area of the tensile test specimen in square millimetres (square inches), based on specified outside diameter or nominal specimen width and specified wall thickness, rounded to the nearest 10 mm^2 (0.01 in^2), or 490 mm^2 (0.75 in^2) whichever is smaller

a for a limit state formula, the maximum actual depth of a crack-like imperfection; for a design formula, the maximum depth of a crack-like imperfection that could likely pass the manufacturer's inspection system

a_N imperfection depth associated with a specified inspection threshold, i.e. the maximum depth of a crack-like imperfection that could reasonably be missed by the pipe inspection system. For example, for a 5 % imperfection threshold inspection in a 12,7 mm (0.500 in) wall thickness pipe, a_N = 0,635 mm (0.025 in)

$a_{t/D}$ average value of t/D ratios used in the regression

B_c empirical constant in historical API collapse formula

B_f maximum bearing face diameter, special bevel, in accordance with ISO 11960 or API 5CT

b Weibull shape parameter

C_c empirical constant in historical API collapse formula

C_{iR} random variable that represents model uncertainty

c tube curvature, the inverse of the radius of curvature to the centreline of the pipe

D specified pipe outside diameter

D_{ac} average outside diameter after cutting

D_{ave} average pipe outside diameter

D_{bc} average outside diameter before cutting

D_{max} maximum pipe outside diameter

D_{min} minimum pipe outside diameter

D_4 major diameter, in accordance with API 5B

d pipe inside diameter, $d = D - 2t$

d_{iu} inside diameter of pin upset, in accordance with ISO 11960 or API 5CT

d_{ou} inside diameter at end of upset pipe

d_{wall} inside diameter based on $k_{wall}\ t$; $d_{wall} = D - 2k_{wall}\ t$

$d1$ diameter at the root of the coupling thread at the end of the pipe in the power-tight position

E	Young's modulus
E_c	pitch diameter, at centre of coupling
E_{ec}	pitch diameter, at end of coupling
E_s	pitch diameter, at plane of seal
E_0	pitch diameter, at end of pipe
E_1	pitch diameter at the hand-tight plane, in accordance with API 5B
E_7	pitch diameter, in accordance with API 5B
ec	eccentricity
e_m	mass gain due to end finishing
F_a	material axial force
F_{eff}	effective axial force; $Feff = Fa - pi\ Ai + po\ Ao$
F_c	empirical constant in historical API collapse formula
F_{YAPI}	material axial force at yield, historical API formula
f	degrees of freedom = $N_t - 1$
$f(\vec{x})$	joint probability density function of the variables in $\vec{x}$
f_{rn}	root truncation of the pipe thread of API line pipe threads, as follows: 0,030 mm (0.001 2 in) for 27 TPI; 0,046 mm (0.001 8 in) for 18 TPI; 0,061 mm (0.002 4 in) for 14 TPI; 0,074 mm (0.002 9 in) for 11-1/2 TPI; 0,104 mm (0.004 1 in) for 8 TPI
f_u	tensile strength of a representative tensile specimen
f_{uc}	tensile strength of a representative tensile specimen from the coupling
f_{umn}	specified minimum tensile strength
f_{umnc}	specified minimum tensile strength of the coupling
f_{umnp}	specified minimum tensile strength of the pipe body
f_{up}	tensile strength of a representative tensile specimen from the pipe body
f_y	yield strength of a representative tensile specimen
f_{yax}	equivalent yield strength in the presence of axial stress
f_{ye}	equivalent yield stress in the presence of axial stress
f_{ymn}	specified minimum yield strength
f_{ymnc}	specified minimum yield strength of the coupling
f_{ymnp}	specified minimum yield strength of the pipe body

f_{ymx} specified maximum yield strength

f_{yp} yield strength of a representative tensile specimen from the pipe body

G_c empirical constant in historical API collapse formula

G_0 influence coefficient for fracture limit state FAD curve

G_1 influence coefficient for fracture limit state FAD curve

G_2 influence coefficient for fracture limit state FAD curve

G_3 influence coefficient for fracture limit state FAD curve

G_4 influence coefficient for fracture limit state FAD curve

g length of imperfect threads, in accordance with API 5B

$g(\bar{x})$ limit state function

H thread height of a round-thread equivalent Vee thread, as follows:
0,815 mm (0.032 1 in) for 27 TPI,
1,222 mm (0.048 1 in) for 18 TPI,
1,755 mm (0.069 1 in) for 14 TPI,
1,913 mm (0.075 3 in) for 11-1/2 TPI,
2,199 6 mm (0.086 60 in) for 10 TPI,
2,749 6 mm (0.108 25 in) for 8 TPI

Ht_{des} decrement factor for design collapse strength, as given in Table F.9

Ht_{ult} a decrement factor for ultimate collapse strength, as defined in Formula (F.4)

h_B buttress thread height: 1,575 for SI units, 0.062 for USC units

h_n stress-strain curve shape factor

h_s round thread height

I moment of inertia of the pipe cross section; $I = \pi/64\ (D^4 - d^4)$

I_{ave} average moment of inertia of the pipe cross section; $I = \pi/64\ [D_{ave}{}^4 - (D_{ave} - 2\ t_{c\ ave})^4]$

I_B length from the face of the buttress thread coupling to the base of the triangle in the hand-tight position: 10,16 mm (0.400 in) for Label 1: 4-1/2; 12,70 mm (0.500 in) for sizes between Label 1: 5 and Label 1: 13-3/8, inclusive; and 9,52 mm (0.375 in) for sizes greater than Label 1: 13-3/8

J distance from end of pipe to centre of coupling in power-tight position, in accordance with API 5B

J_{Ic} fracture resistance of the material

J_{Imat} fracture resistance of the material in a particular environment

J_p polar moment of inertia of the pipe cross section; $J_p = \pi/32\ (D^4 - d^4)$

J_r stress intensity ratio based on the J-Integral

K stress intensity factor at the crack tip