COMPARISON OF
API AND CSA OFFSHORE PIPELINE
STRESS AND STRAIN DESIGN CRITERIA

by

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REFERENCE DOCUMENTS

. **Reference 1, Chapter 11, Offshore Steel Pipelines, CSA Z662-99, Oil and Gas Pipeline Systems**

. **Reference 2, API Recommended Practice 1111, Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design), API RP 1111 Revision Task Force for the 3rd Edition, Final Draft Copy**

. **Reference 3, Chapter 4, Design, CSA Z662-99, Oil and Gas Pipeline Systems**

. **Reference 4, Clause 8.2, Tensile Properties, CAN/CSA-Z245.1-M90, Steel Line Pipe**

. **Reference 5, Clause 11.5.4, Wall Thickness Tolerance, CAN/CSA-Z245.1-M90, Steel Line Pipe**

. **Reference 6, Appendix C, Limit States Design, CSA Z662-99, Oil and Gas Pipeline Systems**

To compare API Recommended Practice (Reference 2) with CSA Standard (Reference 1), an example pipeline has been specified as follows:

- **Specified: Outside Diameter, D = 24.0 in (610 mm)**
- **Specified: Grade 414 steel. For Grade 414 steel:**
  the Yield Strength (minimum) = 60 ksi (414 Mpa), and
  the Tensile Strength (minimum) = 75 ksi (517 Mpa)
- **Modulus of Elasticity of Steel, E = 30,000 ksi**
- **Specified (Internal) Design Pressure, P_d = 1650 psi (11,377 kPa)**

- **Unit Conversion: 1000 psi = 6895 kPa**

Note: Apart from the determination of loads and load effects, the <u>Limit States Design</u> method defined in Reference 6 for the design of pipelines is not applicable to the design of offshore pipelines due to the specification of very restrictive (ie. conservative) <u>strain limits.</u>

HOOP STRESS ANALYSIS - CSA

. In this example, the specified (internal) design pressure will be used to determine the required wall thickness of the pipeline.

. The (internal) design pressure for a given wall thickness or the design wall thickness for a given (internal) design pressure can be determined as follows:

$$P_d = (2)(t)(S)(F_d)(J)(T)/(D) \qquad \text{Formula 1}$$

or

$$t = (P_d)(D)/(2)(S)(F_d)(J)(T) \qquad \text{Formula 2}$$

Note: use of design nominal wall thickness vs design minimum wall thickness:

. For onshore pipeline design, (Reference 4 - CSA), the design wall thickness is the design .nominal wall thickness..

. For offshore pipeline design, (Reference 1 - CSA), the design wall thickness is the design .minimum wall thickness..

. For offshore pipeline design, (Reference 2 - API), the design

wall thickness is the design .nominal wall thickness..

For the example pipeline, it is appropriate to determine the design minimum wall thickness in accordance with CSA

Therefore, substituting into Formula 2 gives

t (minimum)=(1650)psi(24.0)in/(2)(60,000)psi(0.72)(1.0)(1.0)

- **t (minimum) = 0.46 in (0.45833 in) (11.7 mm)**

From Table 11.2 of Reference 5, the minus tolerance on nominal wall thickness can be as high as minus 8%. This implies that:

- **design nominal wall thickness = (design minimum wall thickness)/(0.92)**

Therefore:

t (nominal) = (0.46)/(0.92)

- **t (nominal) = 0.50 in (12.7 mm)**

Note: The nominal wall thickness is that which would be ordered from the manufacturer.

Now, the hoop stress, at any given pressure, is defined by

$$\sigma = (P)(D)/(2)(t) \qquad \text{Formula 3}$$

where

σ = hoop stress, psi

P = internal pressure, psi

D = outside diameter, in

t = nominal or minimum wall thickness, in

Therefore, at the (internal) design pressure, the hoop stress based on <u>minimum</u> wall thickness using Formula 3 should be

$$\sigma_d = (1650)\text{psi}(24.0)\text{in}/(2)(0.45833)\text{in}$$

$$\sigma_d = 43{,}200 \text{ psi } (=72\% \text{ SMYS})$$

And, at the (internal) design pressure, the hoop stress based on nominal wall thickness using Formula 3 is

$$\sigma_d = (1650)\text{psi}(24.0)\text{in}/(2)(0.50)\text{in}$$

$$\sigma_d = 39{,}600 \text{ psi } (=66\% \text{ SMYS})$$

(BURST) PRESSURE DESIGN - API

. **In API RP 1111, a .Limit State Design. approach has been incorporated into the RP to provide a uniform factor of safety with respect to rupture or burst failure as the primary design condition.**

. **In Clause 2.3.1, Reference 2 - API, the hydrostatic test pressure, the internal design pressure, the incidental overpressure and the maximum operating pressure are determined in relation to the calculated minimum burst pressure.**

MINIMUM BURST PRESSURE, P_b

The minimum burst pressure, P_b is determined by one of the following formulae:

$$P_b = 0.45(S+U)\ln(D/D_i) \qquad \text{Formula 4}$$

or

$$P_b = 0.90(S+U)(t/(D-t)) \qquad \text{Formula 5}$$

where

P_b = minimum burst pressure, psi

S = 60 ksi, specified minimum yield strength (SMYS)

U = 75 ksi, specified minimum ultimate tensile strength

t = 0.50 in, nominal wall thickness

D = 24.0 in, outside diameter

Now, for D/t > 15, the two formulae (4 and 5) for the minimum burst pressure are equivalent.

For the example pipeline, D/t = 24.0/0.50 = 48 which is greater than 15.

Therefore, the minimum burst pressure of the pipe can be determined by substituting into Formula 5:

$$P_b = (0.90)(60{,}000+75{,}000)\text{psi}(0.50)\text{in}/(24.0-0.50)\text{in}$$

$$P_b = \underline{2585.1 \text{ psi}}$$

Therefore, at the minimum burst pressure, the equivalent hoop stress based on nominal wall thickness using Formula 3 is

$$ó_b = (2585.1)\text{psi}(24.0)\text{in}/(2)(0.50)\text{in}$$

$$ó_b = 62{,}042 \text{ psi } (\underline{=103\% \text{ SMYS}})$$

HYDROSTATIC TEST PRESSURE, P_t

The hydrostatic test pressure, P_t is given by:

$$P_t = (F_d)(J)(T)(P_b) \qquad \text{Formula 6}$$

where

P_t = hydrostatic test pressure, psi

F_d = 0.90, internal pressure (burst) design factor

J = 1.0, longitudinal weld joint factor

T = 1.0, temperature de-rating factor

P_b = 2585.1 psi, minimum burst pressure

Substituting into Formula 6 gives

$$P_t = (0.90)(1.0)(1.0)(2585.1)\text{psi}$$

$$P_t = \underline{2326.6 \text{ psi}}$$

Therefore, at the hydrostatic test pressure, the equivalent hoop stress based on nominal wall thickness using Formula 3 is

$$ó_t = (2326.6)\text{psi}(24.0)\text{in}/(2)(0.50)\text{in}$$

$ó_t$ = 55,838 psi (<u>=93% SMYS</u>)(CSA: <u>=92% SMYS</u>)

DESIGN PRESSURE, P_d

The design pressure, P_d is given by:

$$P_d = (0.80)(P_t) \qquad \text{Formula 7}$$

where

P_d = design pressure, psi

P_t = 2326.6 psi, hydrostatic test pressure

Substituting into Formula 7 gives

$$P_d = (0.80)(2326.6)\text{psi}$$

$$P_d = \underline{1861.3 \text{ psi}} \text{ (CSA: } \underline{=1650 \text{ psi}}\text{)}$$

Therefore, at the design pressure, the equivalent hoop stress based on nominal wall thickness using Formula 3 is

$$ó_d = (1861.3)\text{psi}(24.0)\text{in}/(2)(0.50)\text{in}$$

$$ó_d = 44{,}670 \text{ psi } (\underline{=74\% \text{ SMYS}})(\text{CSA: } \underline{=66\% \text{ SMYS}})$$

SUMMARY - HOOP STRESS ANALYSIS

. **The specified (internal) design pressure was used as the basis for the pipeline design using Reference 1 - CSA and was specified at a pressure of 1650 psi. The minimum pipe wall thickness was then determined to satisfy CSA.**

. **Using the design nominal wall thickness determined in accordance with the CSA Standard, the design pressure was then determined based on the design method provided in Reference 2 - API. This (maximum allowable) design pressure was calculated to be 1861.3 psi. This value represents a 12.8% (1861.3/1650) higher allowable design pressure using the API Recommended Practice over the CSA Standard. Based on hoop stress analyses and associated stress limits, the API Recommended Practice has a clear advantage over the CSA Standard in that it permits the inherent strength of the pipeline to be more fully utilized during normal pipeline operating conditions (ie. the CSA Standard imposes stress limits which lead to a more conservative design for an offshore pipeline).**

The stress limits of API vs CSA were also compared for several other pipeline provisions including:

MAXIMUM OPERATING PRESSURE (MOP) REQUIREMENTS

COMBINED LOAD/STRESS REQUIREMENTS

HYDROSTATIC TEST PRESSURE REQUIREMENTS

MAXIMUM OPERATING PRESSURE

. **API (Reference 2) - In API , the maximum operating pressure (MOP) should not exceed any of the following:**
a) (Clause 2.2.2.1) the design pressure of the pipe, or
b) (Clause 2.2.2.1) 80% of the applied hydrostatic test pressure.

. **CSA (Reference 1) - In CSA, the maximum operating pressure (MOP) shall be the lesser of either:**
a) (Clause 11.6.3.3) the maximum internal fluid design pressure, or
b) (Clause 11.6.3.3) 80% of the hydrostatic test pressure.

. **The provisions of both API and CSA in respect of maximum operating pressure (MOP) are essentially the same.**

COMBINED LOADS - COMBINED STRESSES

. **API (Reference 2) - In API, the combination of primary axial load and internal pressure load shall not exceed that given by**

$$(((P_i - P_e)/P_b)^{**}2 + (T_e/T_y)^{**}2)^{**}0.5$$.

where

P_i **= internal pressure, psi**

P_e **= external hydrostatic pressure, psi**

P_b **= minimum burst pressure, psi**

T_e **= effective tension in pipe, lbs**

T_y **= yield tension in pipe, lbs**

. **The value of the above expression shall not exceed:**

a) 0.90 for operational loads,

b) 0.96 for extreme loads, and

c) 0.96 for hydrotest loads

Note: The above formula is based on the Tresca hypothesis for combined loads and utilizes the minimum burst pressure in its formulation.

. **CSA (Reference 1) - In CSA, the maximum combined effective stress, S_c based on the design minimum wall thickness, due to all load and load effects shall be determined using the following formula:**

$$S_c = ((S_l)^2 + (S_h)^2 - (S_l)(S_h) + (3)(\hat{o}_{hl}))^{0.5}$$

where

S_c = maximum combined effective stress, ksi

S_l = total longitudinal stresses, ksi

S_h = total hoop stress, ksi

$\hat{o}_{hl}$ = tangential shear stress, ksi

Note: The above formula is an expression of the plasticity hypothesis of Hüber, von Mises, and Hencky and includes the tangential shear stresses in its formulation.

. **The allowable stress, S_{ca} shall be determined using:**

$$S_{ca} = (F)(S)(T)$$

where

F = 1.0, design factor for combined stresses

. **Therefore, for combined stresses, the maximum combined effective stress, S_c shall not exceed the allowable stress, S_{ca} .**

SUMMARY - COMBINED LOADS/STRESSES

. **The provisions of API in respect of combined loads and the provisions of CSA in respect of combined stresses require full consideration of all loads and load effects which may contribute to the maximum hoop stress and to the maximum longitudinal stress.**

. **Although, each of the formulations are based on slightly different combined stress hypothesis, Tresca vs Hüber etc., and different pipe wall thicknesses, nominal vs minimum, if the longitudinal stress contributions are significant, then the allowable maximum operating pressure determined in accordance with the stress limits defined by each design practice will probably be very similar in magnitude.**

. **If however, the longitudinal loads or longitudinal stresses are small or insignificant, then the stress limits established from hoop stress analyses will control the design of the pipeline. Again, this makes the API Recommended Practice somewhat more beneficial in that it allows the inherent strength of the pipeline to be more fully utilized during normal pipeline operating conditions.**

HYDROSTATIC TEST PRESSURE

. **API (Reference 2) - In API , the after-construction strength test (ie., the hydrostatic test pressure):**

a) (Clause 6.2.4.1) should not be less than 125% of the pipeline maximum operating pressure, and

b) (Clause 6.2.4.1) should not result in combined loads exceeding 96% of capacity as described in Clause 2.3.1.2 (Combined Load Design).

. **CSA (Reference 1) - In the CSA standard, pipelines:**

a) (Clause 11.6.3.2) shall be subject to strength test pressures of at least 1.25 times their intended maximum operating pressures, and

b) (Clause 11.2.4.2.1.2.2) shall be designed to withstand strength test pressures in accordance with the requirements of Clause 11.6.3.2 such that, during pressure testing, the maximum combined effective stress shall not exceed the allowable stress (see Clause 11.2.4.2.3). The allowable stress is based on a design factor equal to 1.0 (see Table 11.1).

SUMMARY - HYDROSTATIC TEST PRESSURE

. **The requirements of both API and CSA in respect of hydrostatic test pressures are, in essence, the same since the conclusions drawn in regard to the API provisions for combined loads and the CSA provisions for combined stresses provide approximately the same stress limits.**

Note: Based on nominal wall thickness:

For API: $ó_t$ was calculated to be 93% SMYS

For CSA: $ó_t$ can be as high as 92% SMYS

STRAIN CONSIDERATIONS - STRAIN LIMITS

. **In instances where pipelines:**

-are subject to extremely large deformations which may result from massive slope failures or seabed movements, or

-are subject to extremely large deformations and/or stresses which may result from iceberg/pipeline interaction phenomenon or multi-year ice/pipeline interaction phenomenon, or

-are subject to extremely large dynamic stresses as a result of seismic activity or the possibility of vortex shedding

then, of course, the pipeline does and will fail.

. **However, pipelines are often subject to large inelastic deformations without failure or loss of operational suitability or serviceability and as such may readily be classified to be occurrences of strain-controlled loading.**

. **Strain-controlled loads may arise from seismic activity, frost heave, liquefaction, subsidence, thaw settlement, loss of support (ie. spanning), slope movements and general soil movement of the seabed.**

. **From a practical point of view, strain-controlled loads are not associated with the absorption by the pipeline of excessively large loads or excessively large stresses.**

. **The fundamental principle or philosophy connected with the application of strain-controlled loads is that they normally impart large deflections and/or movements of the pipeline which in turn impose large deformations, that is, deformations of the pipeline which extend into the inelastic range.**

. **These large deformations are then accommodated or absorbed by the inelastic response behaviour of the steel in its inelastic strain range, that is, by imposing large plastic strains into the pipe material.**

STRAIN-CONTROLLED LOADS - API

. **The API recommended practice does not specifically address or define provisions for the design of pipelines subject to large inelastic deformations (ie. strain-controlled loads).**

. **It does however mention in Clause 2.4.2 that the effects of natural phenomena such as earthquakes, hurricanes, cyclones, typhoons and gross sea bottom movement can expose an offshore pipeline to unusual forces and that the design of the pipeline should consider such forces in regard to the stability and safety of the pipeline.**

. **However, the recommended practice provides no specific requirements as to how this may be achieved, and in particular does not deal directly or indirectly with the application of a strain limit in order to allow the operation of the pipeline when it has been subject to large inelastic deformations without failure.**

STRAIN-CONTROLLED LOADS - CSA

. **The CSA standard specifically addresses strain-controlled loads and defines provisions in terms of strain limits.**

Clause 11.2.4.2.1.1, Design Criteria for Installation

. **The CSA standard specifies that for installation, the maximum permissible strain (ie. elastic plus plastic) in the pipe wall, in any plane of orientation, shall not exceed 0.025 (ie. 2.5%).**

. **These strains may be either tensile or compressive in nature and arise in connection with the pipeline installation technique.**

. **Depending on the type of pipeline lay method used to install the pipeline, the plastic strains may vary in magnitude from as little as 1% up to and greater in magnitude than 2%.**

. **Inelastic strains in the order of 1% or more can lead to a local buckling failure mode and as such will control the design of the pipe wall thickness.**

. **To prevent the occurrence of local buckling or wrinkling of the pipeline during installation, the design wall thickness will normally have to be increased.**

Clause 11.2.4.2.2, Design Criteria for Operation

. **The CSA standard specifies that during operation and where strain-controlled loads may occur or exist, the resultant tensile strain (ie. elastic plus plastic), in any plane of orientation in the pipe wall, shall not exceed 0.025 (ie. 2.5%) less any strain residual from installation.**

. **This implies that the total tensile strain, that is the residual tensile strain from installation combined with the tensile strains arising from strain-controlled loads are limited to 2.5% in any plane of orientation in the pipe wall.**

BENEFIT OF CSA STRAIN LIMIT APPROACH

. **The use of a strain limit approach for strain-controlled loads in the CSA standard is a very significant and practical benefit in the design, installation and operation of an offshore pipeline. It is well recognized that offshore pipelines are often subject to loadings and deformations which result in large inelastic strains without failure.**

. **In circumstances where a design standard, code or a recommended practice does not appropriately provide for or even recognize the substantial benefits to be gained in the application of strain limits for the design of the pipeline, it places the pipeline operator in the position of having to implement remedial measures in the form of a removal and replacement.**

. **Such remedial measures may often be unnecessary and subject the pipeline operator to significant unwarranted costs even though the integrity, reliability, serviceability and overall safety of the pipeline may not have been, in any measurable or quantifiable way, impaired or jeopardized.**

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