TMR 4585 Specialization Course UWT
Material selection -Wall thickness design
by

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- **The LRFD concept**
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Material selection process

- **Overall basis:**
  - To assure transport of hydrocarbons an efficient and cost effective way
- **Conceptual design:**
  - Internal conditions: Corrosion – Erosion
  - Corrosion Allowance
  - Linepipe material selection
  - Linepipe material requirements
  - External coating evaluation and selection
  - Corrosion protection preliminary design
- **Detailed design:**
  - Linepipe material definition
  - External coating definition
  - Corrosion protection design
  - Specifications for materials
  - Linepipe/Components/Coating/Anodes
  - Specifications for fabrication

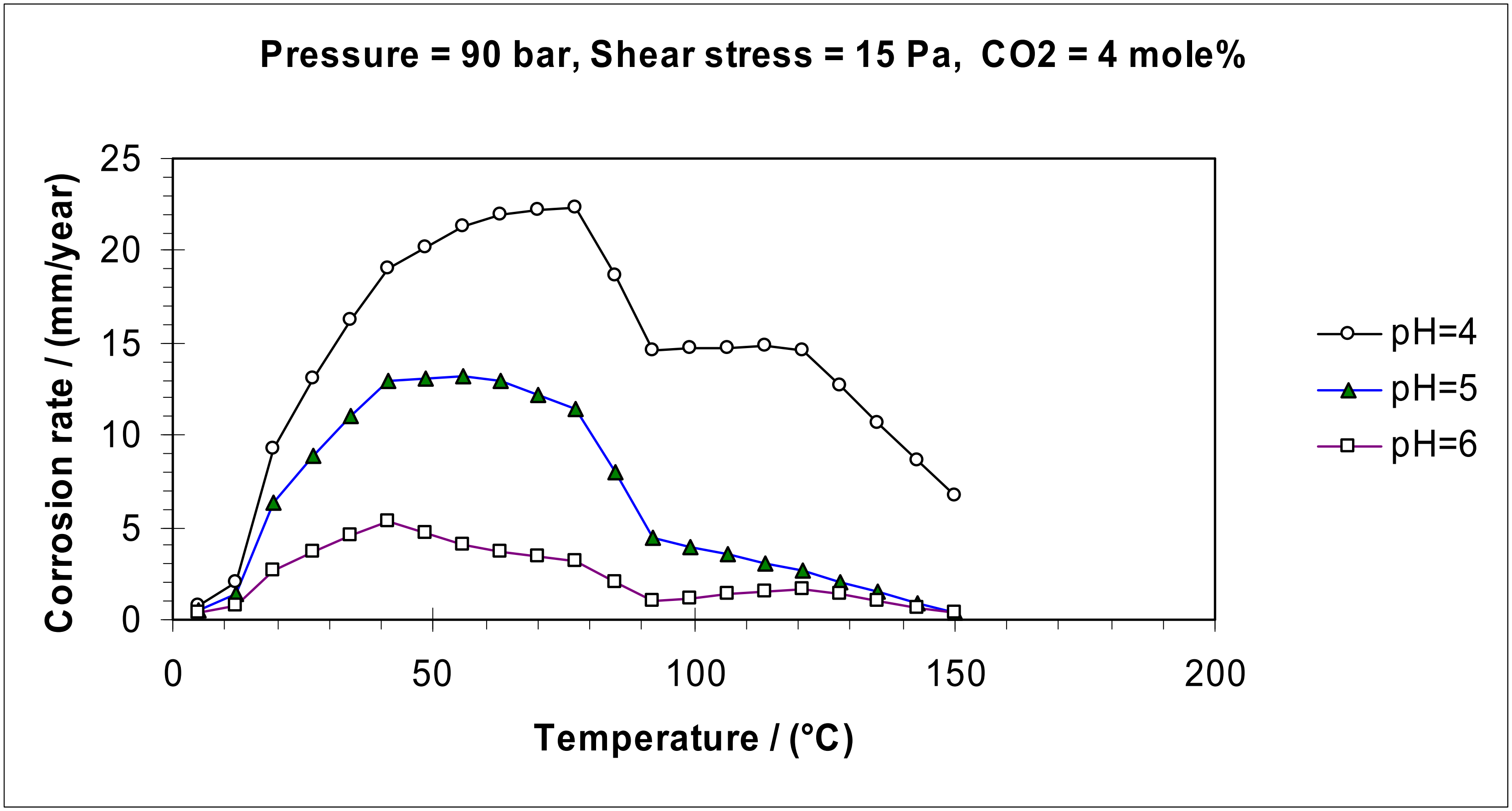
Material selection process

- **Multi-dicipline activity – No ”one-man show”**
- **Process:**
  - Fluid composition/chemistry
  - Production rates for the applicable fluid components
  - Flow types
  - Temperature and pressure (design and operation / min. and max.) profiles
  - Insulation requirements
- **Installation method:**
  - Reel / S-lay / J-lay / Bundle
- **Wall thickness:**
  - Different locations
  - Buckle arrestors
  - Installation
  - Operation

Material selection process – internal corrosion

- **Can Carbon Steel be applied?**
  - what is the required corrosion allowance (CA)?
- **Process data on fluid composition:**
  - Water present?
  - CO2?

Material selection process
NORSOK M- 506 CO2 internal corrosion model



Material selection process – internal corrosion

- **Corrosion rate calculation is only one element in a material selection process.**
- **Other essential factors are uncertainty in input data for corrosion rate calculations,**
  - construction and commissioning conditions,
  - consideration of normal and upset operating conditions,
  - actual corrosivity of produced fluids, scale, wax,
  - inhibitor efficiency and
  - geometry of corrosion attacks.
- **These and other factors may influence the actual corrosion rates considerably, and be more important than any uncertainty in the corrosion rate calculations.**

Material selection process – internal corrosion

- **Evaluation of results as defined in NORSOK M-001 ”Material selection”.**
- **If the corrosion rate resulted in a CA for the design life larger than 10 mm:**
  - Corrosion Resistance Alloy (CRA) to be applied.
- **Can corrosion inhibition be applied or**
  - in case of condensed water, pH stabiliser?
- **This requires a planned corrosion management with corrosion monitoring and corrosion inhibition.**

Material selection process - CRA linepipe

- **In case CRA linepipe is to be selected, the grade shall be defined and candidates are:**
  - 13 % Cr martensitic stainless steel
  - 22 % Cr duplex stainless steel
  - 25 % Cr duplex stainless steel
  - Carbon steel with 316L stainless steel liner
  - Carbon steel with 22 % Cr duplex stainless steel liner
  - Carbon steel with 25 % Cr duplex stainless steel liner
  - Carbon steel with 904L stainless steel liner
  - Carbon steel with Alloy 825 liner
  - Carbon steel with Alloy 625 liner.

Material selection process - LINEPIPE

- **Seamless:**
    - Applicable for Carbon Steel, 13Cr, 22Cr, 25Cr
    - Diameter limited to 16” (18”)
    - Wall thickness up to 50 mm
- **Welded:**
    - Applicable for Carbon Steel, 22Cr, 25Cr
    - Large diameter (from 18” up to 60”-84”)
    - Wall thickness up to 38-50 mm
- **Carbon steel pipe with internal CRA liner:**
    - Clad solution
        - Clad plate (metallurgical bonded CRA)
        - Welded pipe by press bending
    - Lined solution
        - Carbon Steel backing linepipe – Seamless or Welded
        - CRA liner – Welded
- **Carbon steel pipe with internal PE liner**

The concept of limit states to classify load conditions

- Servicability Limit State (SLS), A condition which exceeded renders the pipe unsuitable for operation without necessary causing a leak. For a pipeline, cross-section ovalisation will result from bending. If the ovalisation makes it impossible to carry out planned cleaning by sending cylindrical plugs through the pipeline system (PIG) , then the servicability limit state criterion is exceeded.
- Ultimate Limit State (ULS), A condition which, if exceeded, compromises the integrity of the pipeline.
- Fatigue Limit State (FLS), An ULS condition accounting for accumulated cyclic load effects.
- Accidental Limit State (ALS), An ULS due to accidental (in-frequent) loads.

The LRFD concept

- **Aim: Ref. Offshore Standard DnV-OS-F101 for Offshore Pipelines:**
  - ”Ensure that the concept development, design, construction, operation and abandonment of pipeline systems are safe and conducted with due regard to public safety and the protection of the environment”

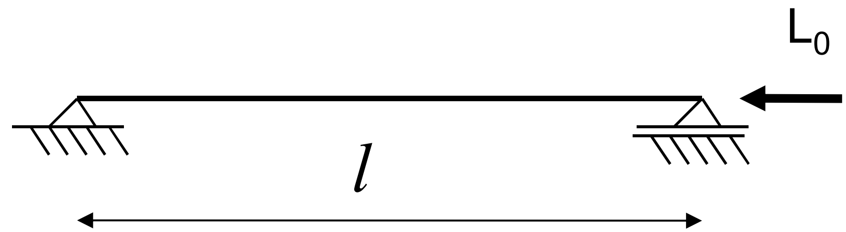
- **Ref. Offshore Standard DnV-OS-F101 for Offshore Pipelines:**
  - LRFD = Load Resistance factored Design format to be checked for Servicability, Ultimate, Fatigue and Accidental limit states (SLS, ULS, FLS and ALS):

$$L_F\gamma_F + L_E\gamma_E + L_I\gamma_I + L_A\gamma_A \leq \frac{R_c}{\gamma_m\gamma_{SC}}$$

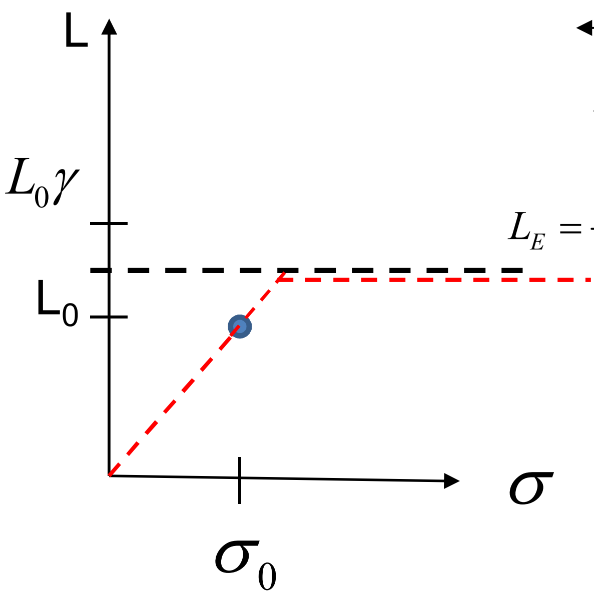
- **API 17J Specification for Unbonded Flexible Pipes:**
  - Allowable Stress Design (ASD) format:

$$\sigma \leq \eta\sigma_F$$

The LRFD concept – versus ASD



$$L_0 = \sigma_0 A \le \eta \sigma_F A = \eta R$$ I am OK?



$$L_E = \frac{\pi^2 EI}{l^2} = Euler\,buckling\,load$$

NO – but that is only picked up by the LRFD format!!

$$L_0\gamma > \frac{R}{\gamma_m \gamma_{SC}}$$

The LRFD concept – Design Procedure

Load model describing the relevant loads **F**

↓

Structural models and analysis procedures to transform **F** into load effect **L** for the different load combinations

↓

Describe the resistance **R** for each failure mode

↓

Perform design checks for each limit state

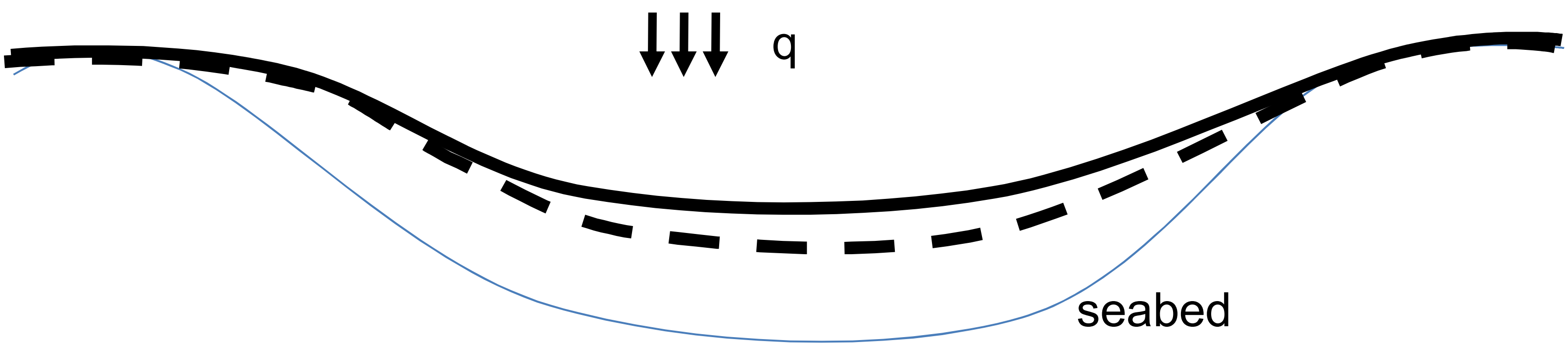
Wall thickness design

- **Primary requirement:**
  - To assure transmittion of hydrocarbons from point A to B in an efficient way
- **Primary structural requirement:**
  - To carry the loads from internal pressure – the hoop stress criterion- **NORMALLY this governs the selection of wall thickness**
- **However, with the additional IMPORTANT constraints:**
  - Excessive yielding during installation and in free spans
  - Local buckling due to bending and external pressure, under installation or operational shut-downs, , **may be governing for wall thickness for deep water applications**
  - Buckle propagation, do not want a buckle to propagate along all installed pipeline due to the pipe being lost in the tensioner during installation
  - Impact loads denting which may cause special protection requirements or increased wall thickness
  - Ovalization, linked to pigging requirement (wax)
  - Fracture due to weld defects may cause leakage during operation or loosing pipe and buckle propagation during installation
  - Fatigue
    - ✓ due to installation vessel motion and wave loads
    - ✓ due to wave loads and current induced VIV motions during operation

The Von Mises yield criterion

- **Combined hoop (circumferential) and longitudinal stresses for control agains excessive yielding:**

$$\sqrt{\sigma_x^2 + \sigma_{\varphi\varphi}^2 - \sigma_x \sigma_\varphi} \le \frac{f_y}{S_f}$$



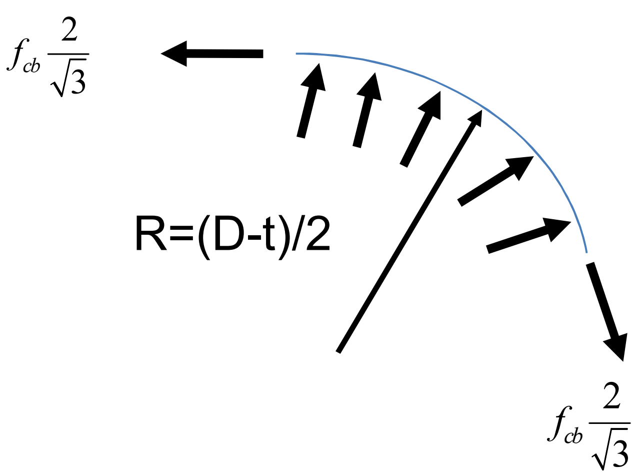
Wall thickness design – The pressure containment (bursting) criterion

- **DnV-OS-101, Submarine Pipeline Systems 2000:**
  - Referred to as pressure containment (bursting):

$$p_i - p_e \le \frac{p_b}{\gamma_m \gamma_{SC}} = \frac{p_b}{S_f}$$

$$p_b \le \frac{2t}{D-t} f_{cb} \frac{2}{\sqrt{3}}$$

$$f_{cb} = Min\left[f_y, \frac{f_u}{1.15} \right]$$



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Classification of fluids

Table 2-1	**Classification of fluids**
Category	*Description*
A	Typical non-flammable water-based fluids.
B	Flammable and/or toxic fluids which are liquids at ambient temperature and atmospheric pressure conditions. Typical examples are oil and petroleum products. Methanol is an example of a flammable and toxic fluid.
C	Non-flammable fluids which are non-toxic gases at ambient temperature and atmospheric pressure conditions. Typical examples are nitrogen, carbon dioxide, argon and air.
D	Non-toxic, single-phase natural gas.
E	Flammable and/or toxic fluids which are gases at ambient temperature and atmospheric pressure conditions and which are conveyed as gases and/or liquids. Typical examples would be hydrogen, natural gas (not otherwise covered under category D), ethane, ethylene, liquefied petroleum gas (such as propane and butane), natural gas liquids, ammonia, and chlorine.

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Classification of location and Safety Classes

C 300 Location classes

301 The pipeline system shall be classified into location classes as defined in Table 2-2.

Table 2-2 Classification of location	
Location	*Definition*
1	The area where no frequent human activity is anticipated along the pipeline route.
2	The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum horizontal distance of 500 m shall be adopted.

C 400 Safety classes

401 Pipeline design shall be based on potential failure consequence. This is implicit by the concept of safety class. The safety class may vary for different phases and locations. The safety classes are defined in Table 2-3.

Table 2-3 Classification of safety classes	
Safety class	*Definition*
Low	Where failure implies insignificant risk of human injury and minor environmental and economic consequences
Medium	Where failure implies low risk of human injury, minor environmental pollution or high economic or political consequences.
High	Classification for operating conditions where failure implies risk of human injury, significant environmental pollution or very high economic or political consequences

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Classification of Safety Classes verus installation and operation load conditions

Table 2-4 Normal classification of safety classes[1)]

Phase	*Fluid Category A, C*		*Fluid Category B, D and E*	
	Location Class		*Location Class*	
	1	2	1	2
Temporary[2,3]	Low	Low	-	-
Operational	Low	Medium[4]	Medium	High

1) Other classifications may exist depending on the conditions and criticality of failure the pipeline. For pipelines where some consequences are more severe than normal, i.e. when the table above does not apply, the selection of a higher safety class shall also consider the implication, on the total gained safety. If the total safety increase is marginal, the selection of a higher safety class may not be justified.

2) Installation until pre-commissioning (temporary phase) will normally be classified as safety class Low.

3) For safety classification of temporary phases after commissioning, special consideration shall be made to the consequences of failure, i.e. giving a higher safety class than Low.

4) Risers during normal operation will normally be classified as safety class High.

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Acceptable failure probabilities vs. Safety Classes

Table 2-5 Nominal annual target failure probabilities per pipeline vs. safety classes[5)]

Limit State Category	*Limit State*	*Safety Classes*			
		Low	*Medium*	*High*	*Very High[4)]*
SLS	All	10^{-2}	10^{-3}	10^{-3}	10^{-4}
ULS ALS	Pressure Containment[1)]	10^{-4} to 10^{-5}	10^{-5} to 10^{-6}	10^{-6} to 10^{-7}	10^{-7} to 10^{-8}
ULS FLS[2)] ALS[3)]	All other	10^{-3}	10^{-4}	10^{-5}	10^{-6}

1) The failure probability for the pressure containment (wall thickness design) is one to two order of magnitudes lower than the general ULS criterion given in the Table, in accordance with industry practice and reflected by the ISO requirements.
2) The failure probability will effectively be governed by the last year in operation or prior to inspection depending on the adopted inspection philosophy.
3) Nominal target failure probabilities can alternatively be one order of magnitude less (e.g. 10^{-4} per pipeline to 10^{-5} per km) for any running km if the consequences are local and caused by local factors.
4) See Appendix F Table F-2.
5) The target shall be interpret as "probability that a failure occurs in the period of one year".

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Definition of pressure

306 *Pressure, Initiation*: The external over-pressure required to initiate a propagating buckle from an existing local buckle or dent (100-year value), see Sec.5 D500.

307 *Pressure, Local; Local Design, Local Incidental* or *Local Test*: In relation to pipelines, this is the internal pressure at any point in the pipeline system or pipeline section for the corresponding design pressure, incidental pressure or test pressure adjusted for the column weight, see Sec.4 B200.

308 *Pressure, Maximum Allowable Incidental (MAIP):* In relation to pipelines, this is the maximum pressure at which the pipeline system shall be operated during incidental (i.e. transient) operation. The maximum allowable incidental pressure is defined as the maximum incidental pressure less the positive tolerance of the Pipeline Safety System, see Figure 1 and Sec.3 D200.

309 *Pressure, Maximum Allowable Operating (MAOP):* In relation to pipelines, this is the maximum pressure at which the pipeline system shall be operated during normal operation. The maximum allowable operating pressure is defined as the design pressure less the positive tolerance of the Pipeline Control System (PCS), see Figure 1 and Sec.3 D200.

310 *Pressure, Mill test* (p_h): The test pressure applied to pipe joints and pipe components upon completion of manufacture and fabrication, see Sec.5 B200.

311 *Pressure, Propagating* (p_{pr}): The lowest pressure required for a propagating buckle to continue to propagate, see Sec.5 D500.

312 *Pressure, shut-in*: The maximum pressure that can be attained at the wellhead during closure of valves closest to the wellhead (wellhead isolation). This implies that pressure transients due to valve closing shall be included.

313 *Pressure, System test* (p_{test}): In relation to pipelines, this is the internal pressure applied to the pipeline or pipeline section during testing on completion of installation work to test the pipeline system for tightness (normally performed as hydrostatic testing), see Sec.5 B200.

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Definition of pressure

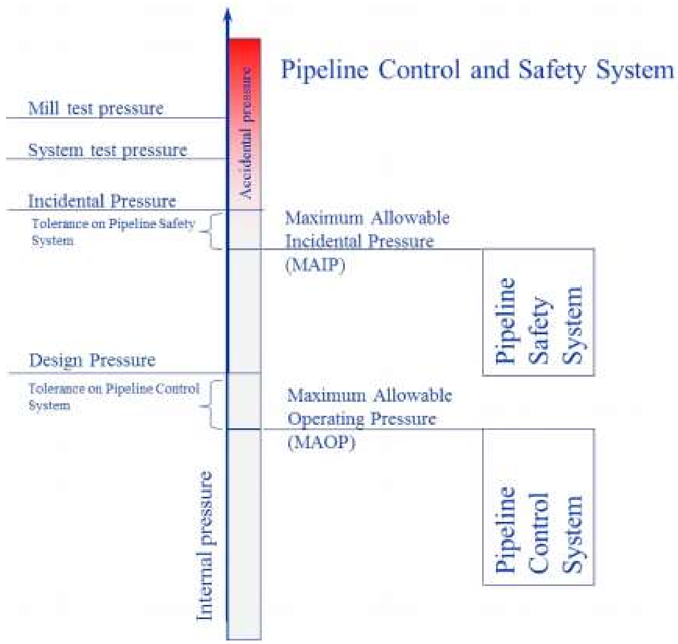

Figure 1
Pressure definitions

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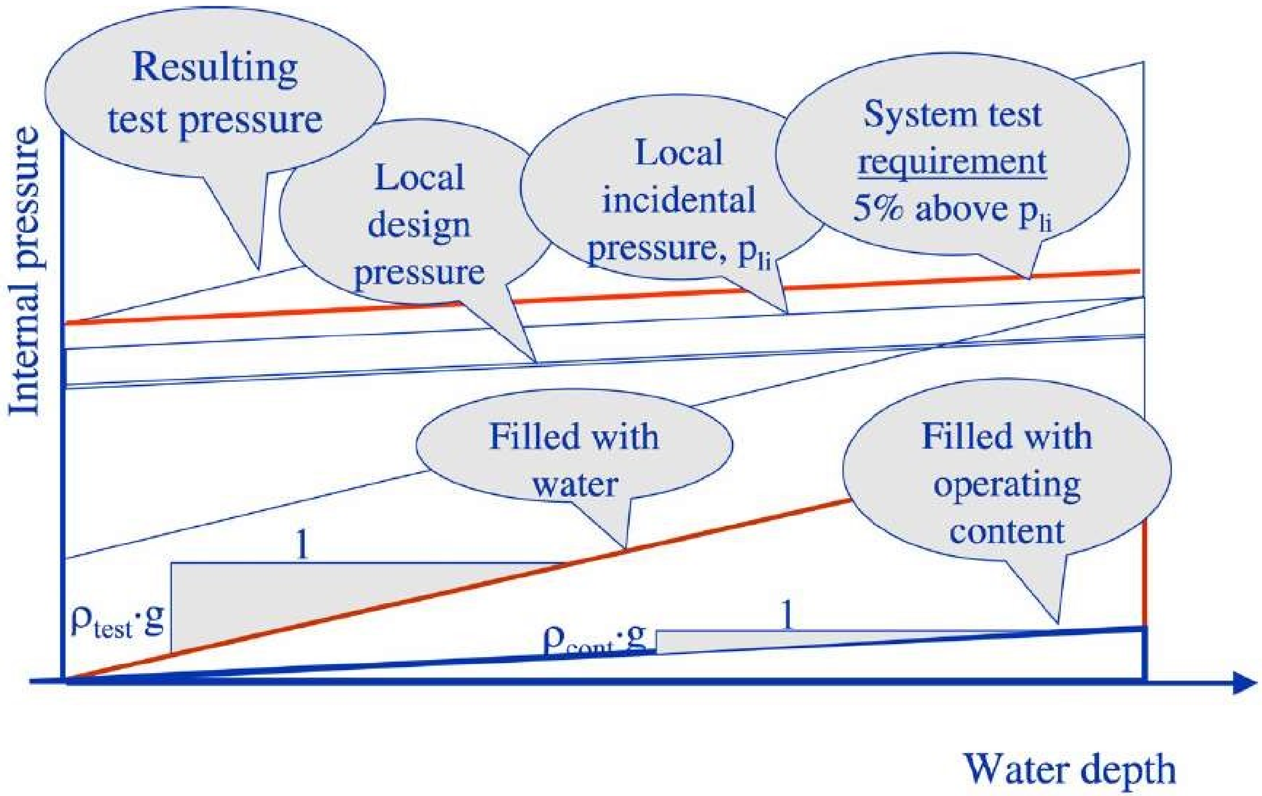
Definition of pressure



e 1

ation of local pressures and requirements to system pressure test

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System Collapse

202 The local pressure is the internal pressure at a specific point based on the reference pressure adjusted for the fluid column weight due to the difference in elevation. It can be expressed as:

$$p_{li} = p_{inc} + \rho_{cont} \cdot g \cdot (h_{ref} - h_l) \qquad (4.1)$$

$$p_{lt} = p_t + \rho_t \cdot g \cdot (h_{ref} - h_l) \qquad (4.2)$$

$$p_{inc} = p_d \cdot \gamma_{inc} \qquad (4.3)$$

where

- p_{li} is the local incidental pressure
- p_{inc} is the incidental reference pressure at the reference elevation
- ρ_{cont} is the density of the relevant content of the pipeline
- g is the gravity
- h_{ref} is the elevation of the reference point (positive upwards)
- h_l is the elevation of the local pressure point (positive upwards)
- p_{lt} is the local system test pressure
- p_t is the system test reference pressure at the reference elevation
- ρ_t is the density of the relevant test medium of the pipeline
- p_d is the design pressure at the pressure reference elevation
- γ_{inc} is the incidental to design pressure ratio

Table 3-1 Incidental to design pressure ratios

Condition or pipeline system	γ_{inc}
Typical pipeline system	1.10
Minimum, except for below	1.05
When design pressure is equal to full shut-in pressure including dynamic effects	1.00

203 In cases where external pressure increases the capacity, the external pressure shall not be taken as higher than the water pressure at the considered location corresponding to low astronomic tide including possible negative storm surge.

204 In cases where the external pressure decreases the capacity, the external pressure shall not be taken as less than the water pressure at the considered location corresponding to high astronomic tide including storm surge.

The pressure containment (bursting) criterion

- **DnV-OS-101, 2012, Submarine Pipeline Systems :**
  - Referred to as pressure containment (bursting):

D 200 Pressure containment (bursting)

201 The pressure containment shall fulfil the following criteria:

$$p_{li} - p_e \leq Min\left(\frac{p_b(t_1)}{\gamma_m \cdot \gamma_{SC}}; \frac{p_{lt}}{\alpha_{spt}} - p_e; \frac{p_h}{\alpha_{mpt} \cdot \alpha_U}\right) \quad (5.6)$$

$$p_{lt} - p_e \leq Min\left(\frac{p_b(t_1)}{\gamma_m \cdot \gamma_{SC}}; p_h\right) \quad (5.7)$$

Unless the mill test has been waived or limited in accordance with Sec.7 E100 or the system test has been waived in accordance with B204. α_{mpt} and α_{spt} are given in Table 5-9.

Table 5-9 Safety class resistance factors, γ_{SC}

	γ_{SC}		
Safety class	*Low*	*Medium*	*High*
α_{mpt} [1]	1,000	1,088	1,251
α_{spt}	1,03	1,05	1,05

1) This factor is given by:

$$\frac{\gamma_m \cdot \gamma_{SC} \cdot 0.96}{2/\sqrt{3}}$$

202 The pressure containment resistance $p_b(t)$ is given by:

$$p_b(t) = \frac{2 \cdot t}{D - t} \cdot f_{cb} \cdot \frac{2}{\sqrt{3}} \quad (5.8)$$

where

$$f_{cb} = Min\left[f_y; \frac{f_u}{1.15}\right] \quad (5.9)$$

Table 5-3 Safety class resistance factors, γ_{SC}

	γ_{SC}		
Safety class	*Low*	*Medium*	*High*
Pressure containment [1]	1.046 [2),3)]	1.138	1.308 [4)]
Other	1.04	1.14	1.26

1) The number of significant digits is given in order to comply with the ISO usage factors.
2) Safety class low will be governed by the system pressure test which is required to be 3% above the incidental pressure. Hence, for operation in safety class low, the resistance factor will effectively be minimum 3% higher.
3) For system pressure test, α_U shall be equal to 1.00, which gives an allowable hoop stress of 96% of SMYS both for materials fulfilling supplementary requirement U and those not.
4) For parts of pipelines in location class 1, resistance safety class medium may be applied (1.138).

p_{li} Local incidental pressure, see Eq. 4.1

p_{lt} Local test pressure (system test), see Eq. 4.2

p_h Mill test pressure at manufacturing plant

Table 5-2 Material resistance factor, γ_m

Limit state category [1)]	*SLS/ULS/ALS*	*FLS*
γ_m	1.15	1.00

1) The limit states (SLS, ULS, ALS and FLS) are defined in D.

The pressure containment (bursting) criterion

- **DnV-OS-101, 2012, Submarine Pipeline Systems :**

C 300 Characteristic material properties

301 Characteristic material properties shall be used in the resistance calculations. The yield stress and tensile strength in the limit state formulations shall be based on the engineering stress-strain curve.

302 The characteristic material strength f_y and f_u, values to be used in the limit state criteria are:

$$f_y = \left(SMYS - f_{y,temp}\right) \cdot \alpha_U \qquad (5.4)$$

$$f_u = \left(SMTS - f_{u,temp}\right) \cdot \alpha_U \qquad (5.5)$$

Where:

$f_{y,temp}$ and $f_{u,temp}$ are the de-rating values due to the temperature of the yield stress and the tensile strength respectively, see 304.

α_U is the material strength factor, see Table 5-4.

306 The material strength factor, α_U, depend on Supplementary requirement U as shown in Table 5-4.

Table 5-4 Material Strength factor, α_U

Factor	*Normally*	*Supplementary requirement U*
α_U	0.96	1.00

Note: For system pressure test, α_U shall be equal to 1.00, which gives an allowable hoop stress of 96% of SMYS both for materials fulfilling supplementary requirement U and those not. This is equivalent to the mill test utilisation.

DnV-OS-101, 2012
Submarine Pipeline Systems

- **Wall thickness classification**

C 400 Characteristic wall thickness

401 Two different characterisations of the wall thickness are used; t_1 and t_2 and are referred to explicitly in the design criteria. Thickness t_1 is used where failure is likely to occur in connection with a low capacity (i.e. system effects are present) while thickness t_2 is used where failure is likely to occur in connection with an extreme load effect at a location with average thickness. These are defined in Table 5-6.

Table 5-6 Characteristic wall thickness

	Prior to operation[1)]	Operation[2)]
t_1	$t-t_{fab}$	$t-t_{fab}-t_{corr}$
t_2	t	$t-t_{corr}$

1) Is intended when there is negligible corrosion (mill pressure test, construction (installation) and system pressure test condition). If corrosion exist, this shall be subtracted similar to as for operation.

2) Is intended when there is corrosion.

402 If relevant, erosion allowance shall be compensated for in the similar way as the corrosion allowance. Minimum wall thickness independent on limit state requirements are given in Table 5-7.

Table 5-7 Minimum wall thickness requirements

Safety Class	*Location class*	*Minimum thickness*
High	2	12 mm unless equivalent protection against accidental loads, other external loads and excessive corrosion is provided by other means. For diameters less than 219 mm (8") minimum wall thickness can be less but shall be determined including the above considerations.

The minimum wall thickness requirement is based on failure statistics, which clearly indicate that impact loads and corrosion are the most likely causes of failure and have the decisive effect on thickness design (not D/t_2).

403 Wall thickness for on bottom stability calculations is given in E502.

Wall thickness design – External pressure buckling

$$\sigma_{max} = \frac{p_e R}{t} + \frac{M_{max}}{t^2/6} = f_y$$

Ovalization: $$\delta_0 = w_1 / R = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

$$EI = \frac{Et^3}{12(1-\nu^2)}$$

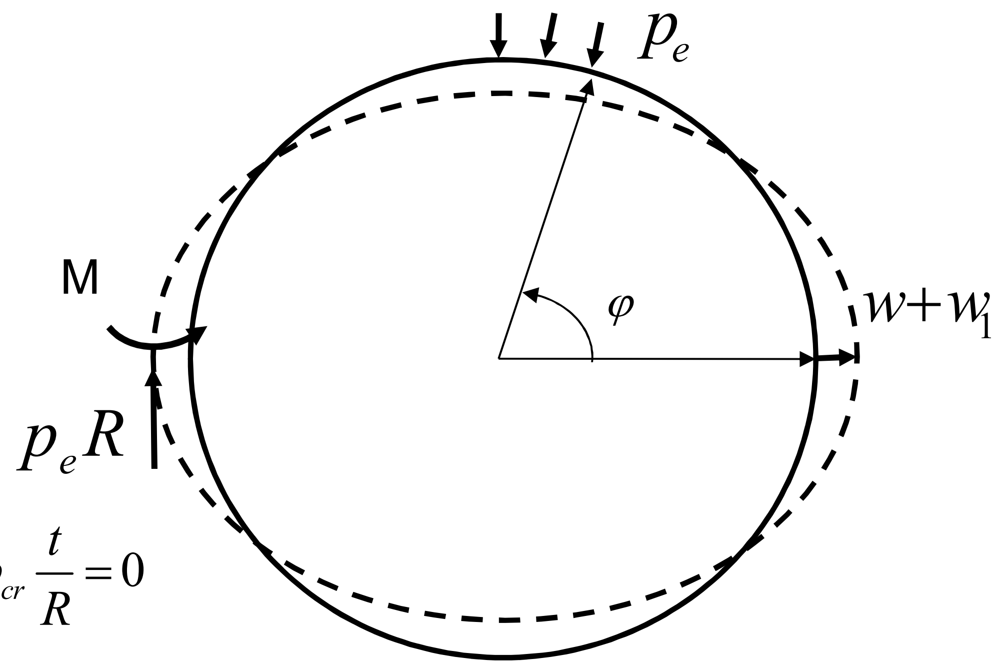
$$\sigma_{max} = \frac{p_e R}{t} + \frac{M_{max}}{t^2/6} = f_y$$

$$M_{max} = (w + w_1 \cos 2\varphi) p_e R$$

$$\frac{\partial^2 w}{\partial \varphi^2} + \left(1 + \frac{p_e R^3}{EI}\right) w = -\frac{w_1 p_e R^2}{EI} \cos 2\varphi$$

$$p_{cr} = \frac{3EI}{R^3} = \frac{E}{4(1-\nu^2)} \left(\frac{t}{R}\right)^3$$

$$p_c^2 - p_c \left[f_y \frac{t}{R} + \left(1 + 6\frac{R}{t}\delta_0\right) p_{cr} \right] + f_y p_{cr} \frac{t}{R} = 0$$



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The collapse equation

D 400 Local Buckling – external over pressure only (system collapse)

401 The external pressure at any point along the pipeline shall fulfil the following criterion (system collapse check):

$$p_e - p_{\min} \leq \frac{p_c(t_1)}{\gamma_m \cdot \gamma_{SC}} \qquad (5.10)$$

402 The characteristic resistance for external pressure (p_c) (collapse) shall be calculated as:

$$(p_c(t) - p_{el}(t)) \cdot (p_c(t)^2 - p_p(t)^2) = p_c(t) \cdot p_{el}(t) \cdot p_p(t) \cdot f_0 \cdot \frac{D}{t} \qquad (5.11)$$

$$p_c^2 - p_c\left[f_y \frac{2t}{D-t} + \left(1 + 3\frac{D-t}{t}\delta_0\right)p_{cr}\right] + f_y p_{cr} \frac{2t}{D-t} = 0$$

where:

Compare!

$$p_{el}(t) = \frac{2 \cdot E \cdot \left(\frac{t}{D}\right)^3}{1 - \nu^2} \qquad (5.12)$$

$$p_p(t) = f_y \cdot \alpha_{fab} \cdot \frac{2 \cdot t}{D} \qquad (5.13)$$

$$f_o = \frac{D_{\max} - D_{\min}}{D} \qquad (5.14)$$

not to be taken < 0.005 (0.5%)

α_{fab} is the fabrication factor, see Table 5-5.

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Buckle propagation:

D 500 Propagation buckling

501 Propagation buckling cannot be initiated unless local buckling has occurred. In case the external pressure exceeds the criterion given below, buckle arrestors should be installed and spacing determined based on cost and spare pipe philosophy. The propagating buckle criterion reads:

$$p_e - p_{min} \leq \frac{p_{pr}}{\gamma_m \cdot \gamma_{SC}} \qquad (5.15)$$

where

$$p_{pr} = 35 \cdot f_y \cdot \alpha_{fab} \left(\frac{t_2}{D} \right)^{2.5} \qquad (5.16)$$

$15 < D/t_2 < 45$

α_{fab} is the fabrication factor, see Table 5-5

Table 5-5 Maximum fabrication factor, α_{fab}

Pipe	*Seamless*	*UO & TRB & ERW*	*UOE*
α_{fab}	1.00	0.93	0.85

Guidance note 1:

Collapse pressure, p_c, is the pressure required to buckle a pipeline.

Initiation pressure, p_{init}, is the pressure required to start a propagating buckle from a given buckle. This pressure will depend on the size of the initial buckle.

Propagating pressure, p_{pr}, is the pressure required to continue a propagating buckle. A propagating buckle will stop when the pressure is less than the propagating pressure.

The relationship between the different pressures are: $p_c > p_{init} > p_{pr}$

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Buckle arrestor design:

502 A buckle arrestor capacity depends on

— propagating buckle resistance of adjacent pipe
— propagating buckle resistance of an infinite buckle arrestor
— length of arrestor.

An integral buckle arrestor may be designed by:

$$p_e \leq \frac{p_X}{1.1 \cdot \gamma_m \cdot \gamma_{SC}} \tag{5.17}$$

where the crossover pressure p_X is

$$p_X = p_{pr} + \left(p_{pr,BA} - p_{pr}\right) \cdot \left[1 - EXP\left(-20 \frac{t_2 \cdot L_{BA}}{D^2}\right)\right] \tag{5.18}$$

$p_{pr,BA}$ is the propagating buckle capacity of an infinite arrestor. This is calculated by Eq. 5.16 with the buckle arrestor properties

L_{BA} buckle arrestor length

Guidance note:

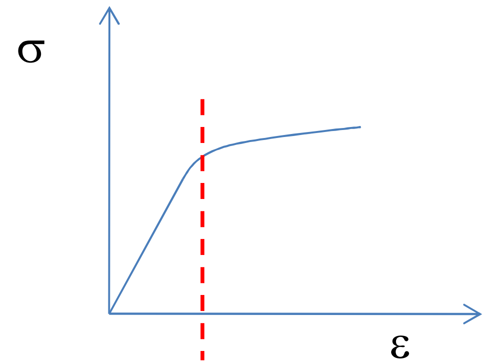
The propagating buckle criterion, Eq. 5.15, corresponds to a nominal failure probability that is one order of magnitude higher than the target nominal failure probability. This is because it is dependent on an initiating even. However, for a buckle arrestor, it is recommended to have a larger confidence and a safety class higher than for the propagating pressure is recommended.

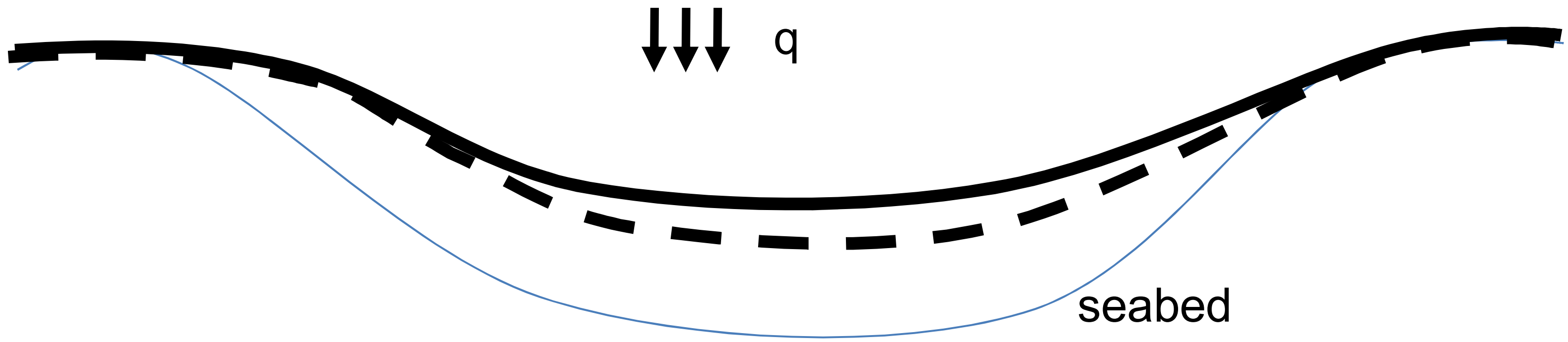
---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

For combined loading:

- **Load controlled condition**

$$f\left(\frac{M}{M_c}, \frac{T}{T_c}, \frac{p}{p_c}\right) \leq 1$$

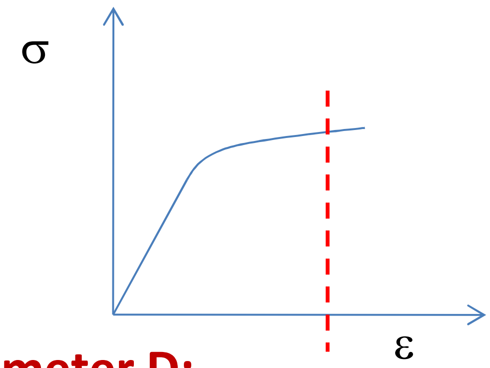




For combined loading:

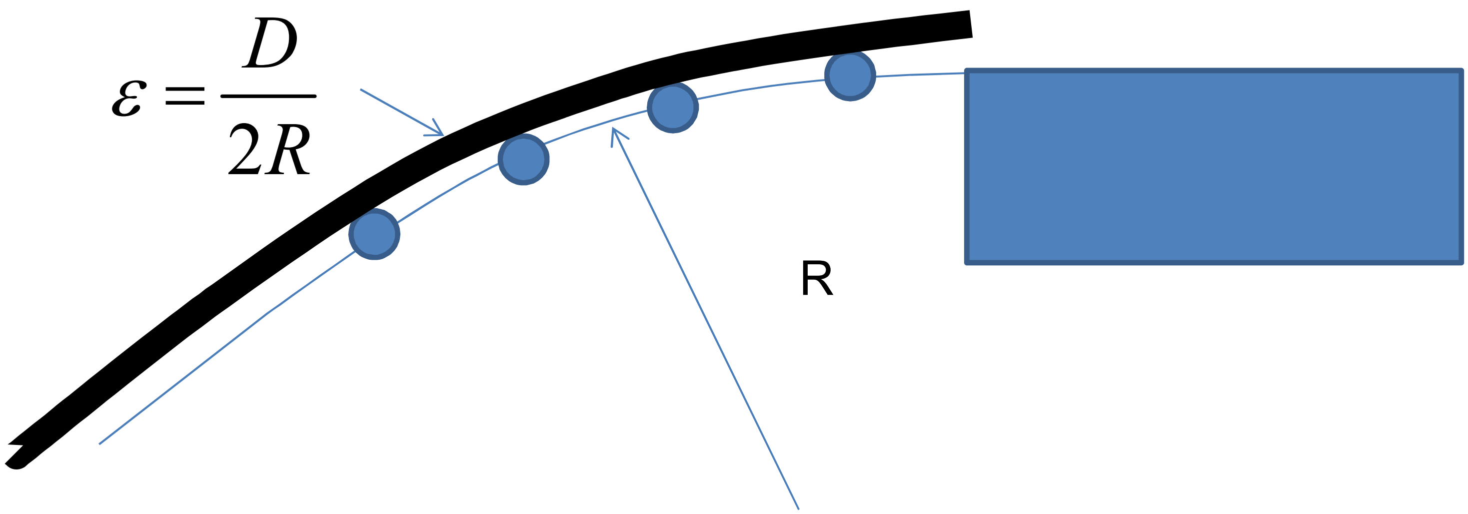
- **Displacement control condition:**

$$f\left(\frac{\varepsilon}{\varepsilon_c}, \frac{p}{p_c}\right) \leq 1$$



- **Outer fibre strain of pipe with diameter D:**

$$\varepsilon = \frac{D}{2R}$$



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- **Combined load condition – Design load effect**

G 300 Design load effect

301 Each limit state, see Sec.5 D, shall be checked for the design load effect.

302 The design load effect can generally be expressed in the following format:

$$L_{Sd} = L_F \cdot \gamma_F \cdot \gamma_c + L_E \cdot \gamma_E + L_I \cdot \gamma_F \cdot \gamma_c + L_A \cdot \gamma_A \cdot \gamma_c \qquad (4.5)$$

In specific forms, this corresponds to:

$$M_{Sd} = M_F \cdot \gamma_F \cdot \gamma_c + M_E \cdot \gamma_E + M_I \cdot \gamma_F \cdot \gamma_c + M_A \cdot \gamma_A \cdot \gamma_c \qquad (4.6)$$

$$\varepsilon_{Sd} = \varepsilon_F \cdot \gamma_F \cdot \gamma_c + \varepsilon_E \cdot \gamma_E + \varepsilon_I \cdot \gamma_F \cdot \gamma_c + \varepsilon_A \cdot \gamma_A \cdot \gamma_c \qquad (4.7)$$

$$S_{Sd} = S_F \cdot \gamma_F \cdot \gamma_c + S_E \cdot \gamma_E + S_I \cdot \gamma_F \cdot \gamma_c + S_A \cdot \gamma_A \cdot \gamma_c \qquad (4.8)$$

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304 The condition load effect factor applies to the conditions in Table 4-5. Condition load effect factors are in addition to the load effect factors and are referred to explicitly in Eq. (4.5, 4.6 and 4.7).

Table 4-5 Condition load effect factors, γ_C

Condition	γ_c
Pipeline resting on uneven seabed	1.07
Reeling on and J-tube pull-in	0.82
System pressure test	0.93
Otherwise	1.00

Table 4-4 Load effect factor combinations

Limit State / Load combination	*Load effect combination*		*Functional loads* [1]	*Environmental load*	*Interference loads*	*Accidental loads*
			γ_F	γ_E	γ_F	γ_A
ULS	*a*	System check[2]	1.2	0.7		
	b	Local check	1.1	1.3	1.1	
FLS	*c*		1.0	1.0	1.0	
ALS	*d*		1.0	1.0	1.0	1.0

1) If the functional load effect reduces the combined load effects, γ_F shall be taken as 1/1.1.

2) This load effect factor combination shall only be checked when system effects are present, i.e. when the major part of the pipeline is exposed to the same functional load. This will typically only apply to pipeline installation.

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- **Combined load condition – Design load effect**

408 The effective axial force that determines the global response of a pipeline is denoted S. Counting tensile force as positive:

$$S(p_i) = N - p_i \cdot A_i + p_e \cdot A_e = N - \frac{\pi}{4} \cdot \left(p_i \cdot (D - 2 \cdot t_2)^2 - p_e \cdot D^2\right) \qquad (4.9)$$

409 Split up into functional, environmental and accidental effective force, the following applies:

$$S_F(p_i) = N_F - p_i \cdot A_i + p_e \cdot A_e = N_F - \frac{\pi}{4} \cdot \left(p_i \cdot (D - 2 \cdot t_2)^2 - p_e \cdot D^2\right) \qquad (4.10)$$

$S_E = N_E$
$S_A = N_A$

410 In the as-laid condition, when the pipe temperature and internal pressure are the same as when the pipe was laid,

$$S = H \qquad (4.11)$$

Where H is the effective (residual) lay tension. The effective residual lay tension may be determined by comparing the as-laid survey data to results from FE analysis.

411 Effective axial force of a totally restrained pipe in the linear elastic stress range is:

$$S = H - \Delta p_i \cdot A_i \cdot (1 - 2 \cdot \nu) - A_s \cdot E \cdot \alpha \cdot \Delta T \qquad (4.12)$$

where:

H = Effective (residual) lay tension
Δp_i = Internal pressure difference relative to as laid
ΔT = Temperature difference relative to as laid.

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- **Combined load condition – Load control – internal overpressure**

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}(p_i)}{\alpha_c \cdot S_p(t_2)}\right\}^2\right\}^2 + \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b(t_2)}\right)^2 \leq 1 \qquad (5.19)$$

Applies for

$15 \leq D/t_2 \leq 45$, $P_i > P_e$, $|S_{Sd}|/S_p < 0.4$

where

M_{Sd}	is the design moment, see Eq. 4.6
S_{Sd}	is the design effective axial force, see Eq. 4.8
p_i	is the internal pressure, see Table 4-3
p_e	is the external pressure, see Sec.4 B200
p_b	is the burst pressure, Eq. 5.8
S_p and M_p	denote the plastic capacities for a pipe defined by:

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- **Combined load condition – Load control – internal overpressure**

$$S_p(t) = f_y \cdot \pi \cdot (D - t) \cdot t \tag{5.20}$$

$$M_p(t) = f_y \cdot (D - t)^2 \cdot t \tag{5.21}$$

$$\alpha_c = (1 - \beta) + \beta \cdot \frac{f_u}{f_y} \tag{5.22}$$

$$\alpha_p = \begin{cases} 1 - \beta & \dfrac{p_i - p_e}{p_b} < \dfrac{2}{3} \\ 1 - 3\beta\left(1 - \dfrac{p_i - p_e}{p_b}\right) & \dfrac{p_i - p_e}{p_b} \geq \dfrac{2}{3} \end{cases} \tag{5.23}$$

$$\beta = \frac{60 - D/t_2}{90} \tag{5.24}$$

α_c is a flow stress parameter and α_p account for effect of D/t_2 ratio.

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- **Combined load condition – Load control – external overpressure**

607 Pipe members subjected to bending moment, effective axial force and external overpressure shall be designed to satisfy the following criterion at all cross sections:

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}}{\alpha_c \cdot S_p(t_2)}\right\}^2\right\}^2 + \left(\gamma_m \cdot \gamma_{SC} \cdot \frac{p_e - p_{\min}}{p_c(t_2)}\right)^2 \le 1 \qquad (5.28)$$

$15 \le D/t_2 \le 45, \quad P_i < P_e, \; |S_{Sd}|/S_p < 0.4$

where

$p_{\min}$ is the minimum internal pressure that can be sustained. This is normally taken as zero for installation except for cases where the pipeline is installed water filled.

p_c is the characteristic collapse pressure, Eq. 5.10. This shall be based on thickness t_2.

Guidance note:

For applications outside the axial load limitations, reference is made to DNV-OS-F201

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