MANUAL

ANALYSIS OF SPANS FOR SUBMERGED PIPELINES

DEP 31.40.10.15-Gen.

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DESIGN AND ENGINEERING PRACTICE

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1. INTRODUCTION

1.1 SCOPE

This new DEP specifies requirements and gives recommendations for the analysis of spans in offshore pipelines including risers and provides guidance for such analyses. Aspects included in this DEP are:

– span analysis methodology;

– design loads to be considered;

– span modelling requirements;

– design equations;

– span acceptance criteria.

Span analysis is necessary to assess the potential for pipeline damage at the location of a span due to:

– possible external loads from activities in the area of the pipelines. Examples of such activities are the anchoring of construction or supply vessels for pipelines in the vicinity of installations and trawling;

– over-stressing and deformations from bending due to weight and hydrodynamic loads;

– fatigue due to vortex-induced vibration (VIV).

NOTES: 1. Operating pressures and temperatures affect the response of a span and also need to be considered during a span analysis.

2. Vortex shedding occurs behind a cylinder when subjected to a lateral current. Oscillating forces, both transverse and in-line with the current, are imposed by this vortex shedding and may cause significant vortex-induced vibrations (VIVs) if the frequency of these forces and the natural frequency of the bending cylinder can align. VIVs can occur in the direction of the current (in-line) or perpendicular to the current direction (cross-flow).

Analysis of span damage due to fatigue from cyclic wave loads is generally not a concern and is therefore not addressed in this DEP.

This DEP can be applied:

- to the design of new pipelines, to provide a design concept which results in the prevention of pipeline span damage at minimum life cycle cost. This requires that all possible span-related costs are addressed, i.e. seabed preparation before pipeline installation (such as seabed levelling) and span correction after construction and/or during operation;
- for the analysis of spans observed from surveys during construction and pipeline operations, in order to decide whether they can be (temporarily) accepted or require correction.

Design equations included in this DEP apply to single-pipe pipeline concepts only. Whilst the basic principles for formulating these design equations apply also to other pipeline concepts such as bundles or pipe-in-pipe pipelines, they differ depending on the selected concept.

Generally applicable definitions and requirements for pipeline engineering can be found in DEP 31.40.00.10-Gen.

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by SIOP and SIEP, the distribution of this DEP is confined to companies forming part of the Royal Dutch/Shell Group or managed by a Group company, and to Contractors nominated by them (i.e. the distribution code is "C", as defined in DEP 00.00.05.05-Gen.).

This DEP is intended for use on offshore pipelines.

If national and/or local regulations exist in which some of the requirements may be more stringent than in this DEP, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable as regards safety, environmental, economic and legal aspects. In all cases, the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned with the object of obtaining agreement to follow this DEP as closely as possible.

1.3 DEFINITIONS

1.3.1 General definitions

The **Contractor** is the party which carries out all or part of the design, procurement, construction, commissioning or management of a project, or operation or maintenance of a facility. The Principal may undertake all or part of duties of the Contractor.

The **Manufacturer/Supplier** is the party which manufactures or supplies equipment and services to perform the duties supplied by the Contractor.

The **Principal** is the party which initiates the project and ultimately pays for its design and construction. The Principal will generally specify the technical requirements. The Principal may include an agent or consultant authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.3.2 Specific definitions

Span - section of a submerged pipeline not in contact with the seabed over its length.

1.4 ABBREVIATIONS

SMYS - Specified minimum yield strength

VIV - Vortex-induced vibrations.

1.5 SYMBOLS

α	linear thermal expansion coefficient for the pipeline steel	$°C^{-1}$
δ	logarithmic decrement of damping of the span in air	-
ρ	density of the seawater	kg/m^3
ν	Poisson's ratio	-
a	frequency factor	-
b	Euler constant	-
A	cross-sectional area of the steel pipe based on nominal wall thickness	m^2
d	fatigue damage	-
ID	internal pipeline diameter	m
E	Young's modulus	N/m^2
f_1	first natural frequency of span	s^{-1}
G	the average gap between the seabed and the bottom of the spanning pipe along the central one-third of the span	m
I	moment of inertia of the pipe	m^4
k	deflection coefficient calculated in accordance with (equation 5.1)	-
K_c	Keulegan-Carpenter number	-
K_s	stability parameter	-
L	span length	m
M	bending moment in pipe	Nm
m_e	effective mass per unit length of pipeline including added mass and mass of pipe content	kg/m
n	predicted number of stress cycles	-
N_e	effective axial compressive force in pipeline (see equation 2.1)	N

n_f	number of stress cycles resulting in pipeline failure due to fatigue	-
N_i	residual axial tension in the pipeline from installation	N
OD	outside diameter of pipeline including coating(s)	m
OD_{st}	nominal outside diameter of the steel pipe	m
P_i	maximum allowable operating pressure	N/m^2
ΔT	difference, at the location of the span, between the predicted maximum pipeline operating temperature and the pipe temperature during installation	°C
T_s	wave period associated with the significant wave	s
V_c	steady current velocity perpendicular to the pipe, at top of pipe level	m/s
V_r	reduced velocity	-
V_w	wave-induced velocity, perpendicular to the pipe at top of pipe level	m/s
W	force, per unit length of pipeline, resulting from the combined weight and hydrodynamic loads	N/m
y	mid-span span deflection due to in-line VIV	m

1.6 CROSS-REFERENCES

Where cross-references to other parts of this DEP are made, the referenced section number is shown in brackets. Other documents referenced in this DEP are listed in (8).

2. METHOD OF ANALYSIS

2.1 PROCEDURE

(Figure 1) schematises the recommended procedure for the analysis of spans of submerged pipelines outlined below.

The assessment of possible external loads is the first step of the analysis after the necessary input data have been collected.

Spans which pass the external load assessment should then be subjected to a preliminary assessment involving a relatively simple analysis based on conservative assumptions. In this analysis spans are considered acceptable if:

- the analysis of reduced velocities indicates that VIVs will not occur and that, consequently, fatigue damage from these vibrations can be ruled out; and
- the calculated maximum combined stresses stay within the limits for elastic stresses in DEP 31.40.00.10-Gen.

Spans which fail the preliminary assessment may still be acceptable if unacceptable damage and/or failure of the span can be ruled out with a more detailed assessment removing some of the conservatism of the preliminary assessment. Spans subjected to the detailed assessment are acceptable if:

- the fatigue assessment demonstrates that fatigue damage from vortex-induced vibrations will not lead to failure during the design or remaining operating lifetime of the pipeline or until the span can be corrected; and
- limits for acceptable plastic strain are not exceeded.

NOTE: Spans have traditionally been assessed against the criteria of the preliminary assessment only. Recent hydrodynamic research on the effect of currents and waves on spanning pipelines has, however, provided information necessary to cautiously quantify stress fluctuations from vortex-induced vibrations. Similarly, research on post-elastic behaviour of pipelines demonstrates that straining of the pipeline beyond the elastic limits can be permitted without impairing the safety of the pipeline.

The requirements, criteria and guidance for each of the above assessments are given in Sections (3) to (7) of this DEP.

Sections (2.2) and (2.3) specify the load conditions and requirements for span modelling to be considered for these assessments.

The length of the span is the critical parameter. Span corrections to reduce the span's length are normally done by dumping rock or seabed material along the entire span, or providing supports along the span. Other methods are water jetting of supports to lower the span into the seabed, or (on sandy seabeds) the placing of artificial seaweed to draw sand into the gap. Requirements for long-term stability should be a main consideration when selecting span rectification method(s).

2.2 LOAD CONDITIONS

Pipeline spans shall be addressed for all phases of the pipeline life cycle. (Table 1) shows these phases with the pipeline condition and design loads which shall be considered for span analyses.

Table 1 Pipeline conditions and design loads

Phase	Pipeline condition	Design loads
Construction	- empty pipeline	- residual construction loads - submerged empty pipeline weight - hydrodynamic loads
	- flooded pipeline (see NOTE)	- residual construction loads - submerged flooded pipeline - hydrodynamic loads
Hydrotesting	- pipeline under test pressure, filled with test medium	- residual construction loads - submerged pipeline filled with test medium - hydrodynamic loads - test pressure
Operation	- operating condition	- residual construction loads - submerged pipeline filled with fluid - hydrodynamic loads - pipeline operating pressure - maximum operating temperature
	- flooded pipeline (see NOTE)	- residual construction loads - submerged flooded pipeline - hydrodynamic loads

NOTE: The flooded pipeline case shall be considered to prevent damage in case of accidental pipeline flooding.

Loads for calculating maximum stresses or strains for comparison with maximum allowable values should be based on:

- the maximum allowable operating pressure for the pipeline;
- maximum pipeline operating temperature predicted at the location of the span;
- maximum fluid density;
- design currents and maximum waves associated with the relevant return period.

Loads for calculating whether VIVs can occur and for fatigue damage calculation should be based on:

- pipeline operating pressure, temperature and fluid density predicted for the location of the span under planned operating conditions;
- design currents and significant waves associated with the relevant return period.

The return period for the hydrodynamic loads should be taken as not less than indicated below:

Case	Return period
Design of safe spans for the pipeline lifetime	100 years
Assessment following survey during construction or operations	1 year if span is discovered during summer season and rectified during same summer season; or 10 years if span will be rectified within one year of discovery except when discovered and rectified as indicated above; or 100 years if span will not be rectified.

2.3 SPAN MODELLING

2.3.1 Simple beam model

Spans in pipelines on an undulating seabed or at a location of local scour or seabed depression may be modelled as simple beams with fixed-pinned boundary conditions and subjected to uniform lateral forces along the span from the combined weight and hydrodynamic loads and to the effective axial compressive force, N_e, see (Figure 2).

Spans which result from the pipeline being lifted off the seabed due to the presence of rock, boulders, debris, etc. should be modelled in accordance with a model appropriate for the specific span.

For axially restrained lines, the effective axial compressive force (N_e) should take into account the pipe contraction from the internal pressure due to the Poisson effect and the expansion due to temperature differentials. The effective axial compressive force for restrained lines is:

$$N_e = (1 - 2\nu)\frac{P_i \,.\, \pi \,.\, D_i^{\,2}}{4} + \alpha \,.\, \Delta T \,.\, A \,.\, E - N_i \qquad \text{(equation 2.1)}$$

where:

- α is the linear thermal expansion coefficient for the pipeline steel
- ν is Poisson's ratio
- A is the cross-sectional area of the steel pipe based on nominal pipe wall thickness
- ID is the internal pipeline diameter
- E is Young's modulus
- N_i is the residual axial tension in the pipeline from installation
- P_i is the operating pressure selected in accordance with (2.2)
- ΔT is the difference at the location of the span between the maximum pipeline operating temperature and pipe temperature during installation.

NOTE: The effective axial force N_e is positive when the force is compressive.

Sagging will cause the length of a spanning pipe to increase and effectively cause the pipe to be tensioned. For pipelines in operation, this results in a decrease in the effective axial compressive force calculated in accordance with (equation 2.1). The beneficial effect of this tensioning on the permissible span length may be taken into account provided the feed-in from sections adjacent to the span, caused by the imbalance of axial forces, is also considered.

Interaction of spans may be neglected if the pipeline length resting on the seabed to the adjacent span is 20% or more of the length of the span being analysed. The length of the span should be increased by 0.2 times the length of the adjacent span if this distance is less.

2.3.2 Finite element model

Finite element modelling of the span permits the removal of some of the conservatism inherent with the simplified beam modelling. Finite element modelling enables the pipe-seabed interaction to be modelled to include the beneficial effect of additional pipe settlement near the span ends and allows the effect of span tensioning due to sagging to be modelled. As with simple beam models, axial feed-in from pipeline sections adjacent to the span should also be modelled if the effect of pipe tensioning due to span sagging is included in the analysis.

3. EXTERNAL LOAD ASSESSMENT

Except for areas in the vicinity of platforms or other installations, trawling is normally the only potential external load to be considered when reviewing permissible spans. The effect of the height of a span on trawlgear loads shall be addressed. Span heights shall be limited to prevent hooking of trawlgear.

Pipeline stresses and/or strains predicted from external loads shall meet the requirements of DEP 31.40.00.10-Gen. unless it is demonstrated that the likelihood of such loads occurring is small and the consequences of pipeline failure acceptable.

Spans should not be permitted in areas near platforms where cables or chains for the anchoring of supply vessels may be run frequently.

4. REDUCED VELOCITY ASSESSMENT

Fatigue damage from both in-line and cross-flow VIVs will be prevented if the margin between the frequency of the shedding vortices and lowest natural frequency of the span is sufficient to prevent "lock in" of those frequencies. It may be assumed that lock-in will not occur if:

$$V_r = \frac{V_c + V_w}{f_n . OD} \leq 1.0 \qquad \text{(equation 4.1)}$$

where:

- V_r is the calculated reduced velocity
- V_c is the steady current velocity perpendicular to the pipe at top of pipe level
- V_w is the wave-induced velocity perpendicular to the pipe at top of pipe level
- f_1 is the first natural frequency of the span.

For the calculation of V_r, the wave-induced velocity V_w may be based on the significant wave.

The contribution of the wave-induced current (V_w) in (equation 4.1) may be ignored for significant waves with a Keulegan-Carpenter number (K_c) less than 30.

The Keulegan-Carpenter number is calculated from:

$$K_c = \frac{V_w . T_s}{OD} \qquad \text{(equation 4.2)}$$

where:

- T_s is the period associated with the significant wave.

The first natural frequency of a simple beam span model subjected to an effective axial compressive force N_e is:

$$f_n = \frac{a}{2\pi}\sqrt{\frac{E.I}{M_e . L^4}\left(1 - \frac{N_e . L^2}{b\pi^2 . E.I}\right)} \qquad \text{(equation 4.3)}$$

where:

- a is the frequency factor
- b is the Euler constant
- I is moment of inertia of the pipe
- L is the span length
- m_e is the effective mass of the pipeline (including content and added mass) per unit length.

Values for the frequency factor a and Euler constant b depend on the end condition of the span:

End condition	Frequency factor a	Euler constant b
Pinned - pinned	9.87	1.
Fixed - pinned	15.4	2.05
Fixed - fixed	22.0	4.

Fixed-pinned end conditions may be assumed for single spans. Fixed-fixed end conditions may only be assumed if validated by the observed support conditions. The support conditions in the case of multiple spans shall be based on sound engineering judgement.

The mass of displaced volume of (sea)water may be assumed for the added mass when calculating the effective pipeline mass.

In-line VIVs are unlikely to occur also in narrow gaps between the seabed and bottom of the pipeline or if the stability parameter (K_s), reflecting the structural damping of the span, exceeds 1.8. The possibility of fatigue damage from in-line VIVs may therefore be ignored if:

$$\frac{G}{OD} \leq 0.25 \,.\, OD \quad \text{or} \qquad \text{(equation 4.4)}$$

$$K_s = \frac{2 \,.\, M_e \,.\, \delta}{\rho \,.\, OD^2} \geq 1.8 \qquad \text{(equation 4.5)}$$

where:

- δ is the logarithmic decrement of damping of the span in air
- ρ is the density of the seawater
- G is the average gap between the seabed and the bottom of the spanning pipe along the central one-third length of the span
- K_s is the stability parameter.

Application of equation (4.4) or (4.5) to rule out in-line VIVs requires an additional criterion to rule out the effects of cross-flow VIVs. It may be assumed that the effects of VIVs in this direction can be ignored if:

$$V_r = \frac{V_c + V_w}{f_n \,.\, OD} \leq 4.7 \qquad \text{(equation 4.6)}$$

In (equation 4.6), the contribution of the wave-induced current V_w may be ignored for significant waves with a Keulegan-Carpenter number less than 6.

5. STATIC STRESS ASSESSMENT

Weight and environmental loads shall be determined in accordance with accepted engineering practices and the resulting bending stresses are then determined. Equivalent stresses shall be calculated taking into account these bending stresses, other axial stresses and
the hoop stress and be verified against the criteria for permissible stresses in DEP 31.40.00.10-Gen.

For calculating bending stresses in spans subjected to an effective axial compressive force (N_e >0), the maximum bending moment in a span may be approximated by:

End condition	Maximum bending moment
Pinned - pinned	$\frac{W}{k^2}\left[\frac{1}{\cos(k.L/2)}-1\right]$
Pinned - fixed	$\frac{W.L}{k}.\frac{\tan k.L.\left[\tan(k.L/2)-k.L/2\right]}{\tan k.L-k.L}$
Fixed - fixed	at support: $\frac{W}{k^2}\left[1-\frac{k.L/2}{\tan(k.L/2)}\right]$
	at centre of span: $\frac{W}{k^2}\left[\frac{k.L/2}{\sin(k.L/2)}-1\right]$

where:

k is the deflection coefficient to be calculated from the following:

$$k=\sqrt{\frac{N_e}{E.I}} \qquad \text{(equation 5.1)}$$

For a pipeline in which the effective axial tension is zero, the maximum bending moment may be calculated from:

End condition	Maximum bending moment
Pinned-pinned	$\frac{W.L^2}{8}$
Pinned-fixed	$\frac{W.L^2}{8}$
Fixed-fixed	$\frac{W.L^2}{12}$

6. FATIGUE ASSESSMENT

6.1 FLOW-INDUCED VIBRATIONS DUE TO VORTEX SHEDDING

6.1.1 Conditions for permitting flow-induced vibrations

In-line VIVs may be permitted provided:

- a safety margin of at least 10 (ten) is maintained between the predicted fatigue damage and the fatigue damage at which the pipeline will fail; and
- they do not occur in risers including the subsea connections to the pipeline resting on the seabed and at locations where intensification of the fluctuating bending stress may occur.

Cross-flow vibrations should not be permitted.

NOTES: 1. The above safety factor of ten reflects the fact that subsea pipelines cannot be inspected for the presence of fatigue damage.

2. Examples of sources for the intensification of bending stresses are fittings, flanges, mechanical connectors and ancillaries welded to the pipeline.

3. The occurrence and amplitude of cross-flow vibrations are difficult to predict. Stresses from cross-flow vibrations can lead to rapid pipeline failure.

6.1.2 Span response from in-line VIVs

Fatigue damage due to in-line flow-induced vibrations shall be assessed if the following three conditions are satisfied:

$$1.0 \le V_r = \frac{V_c + V_w}{f_n \, . \, OD} \le 3.5 \text{ ; and} \qquad \text{(equation 6.1)}$$

$$G \ge 0.25 \, . \, OD \text{ ; and} \qquad \text{(equation 6.2)}$$

$$K_s = \frac{2 \, . \, M_e \, . \, \delta}{\rho \, . \, OD^2} \le 1.8 \qquad \text{(equation 6.3)}$$

NOTE: In-line VIVs are unlikely to occur if any of these conditions are not met.

As in the reduced velocity assessment (4), the contribution of the wave-induced current in (equation 4.1) may be ignored for significant waves with a Keulegan-Carpenter number of less than 30.

The following may be assumed for the response of the span from in-line vibrations:

- the span will respond with a frequency equal to the first natural frequency of the span;
- the maximum mid-point deflection y of the pipeline span may be obtained from (Figure 3).

The total bending stress range due to in-line VIV oscillations with an amplitude y may be calculated as follows:

End condition	Maximum bending stress
Pinned - pinned	$\frac{\pi^2}{L^2} \, . \, y \, . \, E \, . \, OD_{st}$
Fixed - pinned	$\frac{3\pi^2}{4L^2} \, . \, y \, . \, E \, . \, OD_{st}$
Fixed - fixed	$\frac{\pi^2}{2L^2} \, . \, y \, . \, E \, . \, OD_{st}$

where:

OD_{st} is the nominal outside diameter of the steel pipe.

6.1.3 Preventing cross-flow VIVs

Cross-flow VIVs may be assumed not to occur if (equation 4.6) is satisfied.

6.1.4 Fatigue assessment

The fatigue damage of a span over a given period is determined as follows:

- determine the total time that the span may be subjected to in-line VIVs;
- calculate the natural frequency of the in-line VIV;
- calculate the total number of stress cycles n due to VIVs;
- calculate the stress fluctuation per stress cycle (is twice the amount calculated with the equations given in (6.1.2));
- determine from a representative fatigue curve the number of cycles n_f that would result in pipeline failure;
- calculate the factigue damage $d = \frac{n}{n_f}$

The span is acceptable if the fatigue damage does not exceed 0.1.

If the calculated fatigue damage exceeds 0.1, then the span should be corrected within a period during which the fatigue damage does not exceed 0.1.

In the above, the number of cycles n_f until fatigue failure should be reduced if the pipeline has been subjected to previous stress cycles, e.g. from earlier spanning. Miner's rule may be used to calculate the reduction in stress cycles remaining until pipeline failure by fatigue.

7. STRAIN-BASED ASSESSMENT

The static stress assessment (5) may be replaced by a strain-based strength assessment provided the bending of the span is restricted by the seabed before:

- bending strain can cause fracture;
- compressive strain can cause wrinkling or buckling of the pipe;
- pipe ovalisation can exceed 2.5%.

A further requirement for permitting strain is that cyclic straining cannot occur. Variations in operating pressures, temperatures and fluid densities and hydrodynamic loads should all be considered when determining the total possible strain cycle.

NOTE: To prevent fracture, the maximum value for the permissible total strain is 0.5% unless it is demonstrated that for the selected steel and weld properties a higher value may be used.

8. REFERENCES

In this DEP reference is made to the following publications:

NOTE: Unless specifically designated by date, the latest edition of each publication shall be used, together with any amendments/supplements/revisions thereto.

SHELL STANDARDS

Index to DEP publications and standard specifications	DEP 00.00.05.05-Gen.
Pipeline engineering	DEP 31.40.00.10-Gen.

BRITISH STANDARDS

Code of Practice for Pipelines, Part 3: Pipelines Subsea: Design, Construction and Installation	BS 8010-3 (1993)

Issued by:
British Standards Institution
389 Chiswick High Road
London W4 4AL
UK.

NORWEGIAN STANDARDS

Rules for Submarine Pipeline Systems. Det Norske Veritas (1981).	DnV 1981

Issued by:
Det Norske Veritas Industri Norge AS
PO Box 300, N-1322 Høvik
Norway.

9. BIBLIOGRAPHY

NOTE: The following documents are for information only and do not form an integral part of this DEP

1. "Dynamics of marine structures: Methods of calculating the dynamic response of fixed structures subject to wave and current action"; Report UR8 (2nd Edition), CIRIA Underwater Engineering Group — ISSN: 0 86017 101/9

2. Celant M., Re G., Venzi S., Fatigue Analysis for Submarine Pipelines, Offshore Technology Conference, Houston, Paper No. 4233 (1982).

FIGURES

FIGURE 1 SPAN ANALYSIS PROCEDURE

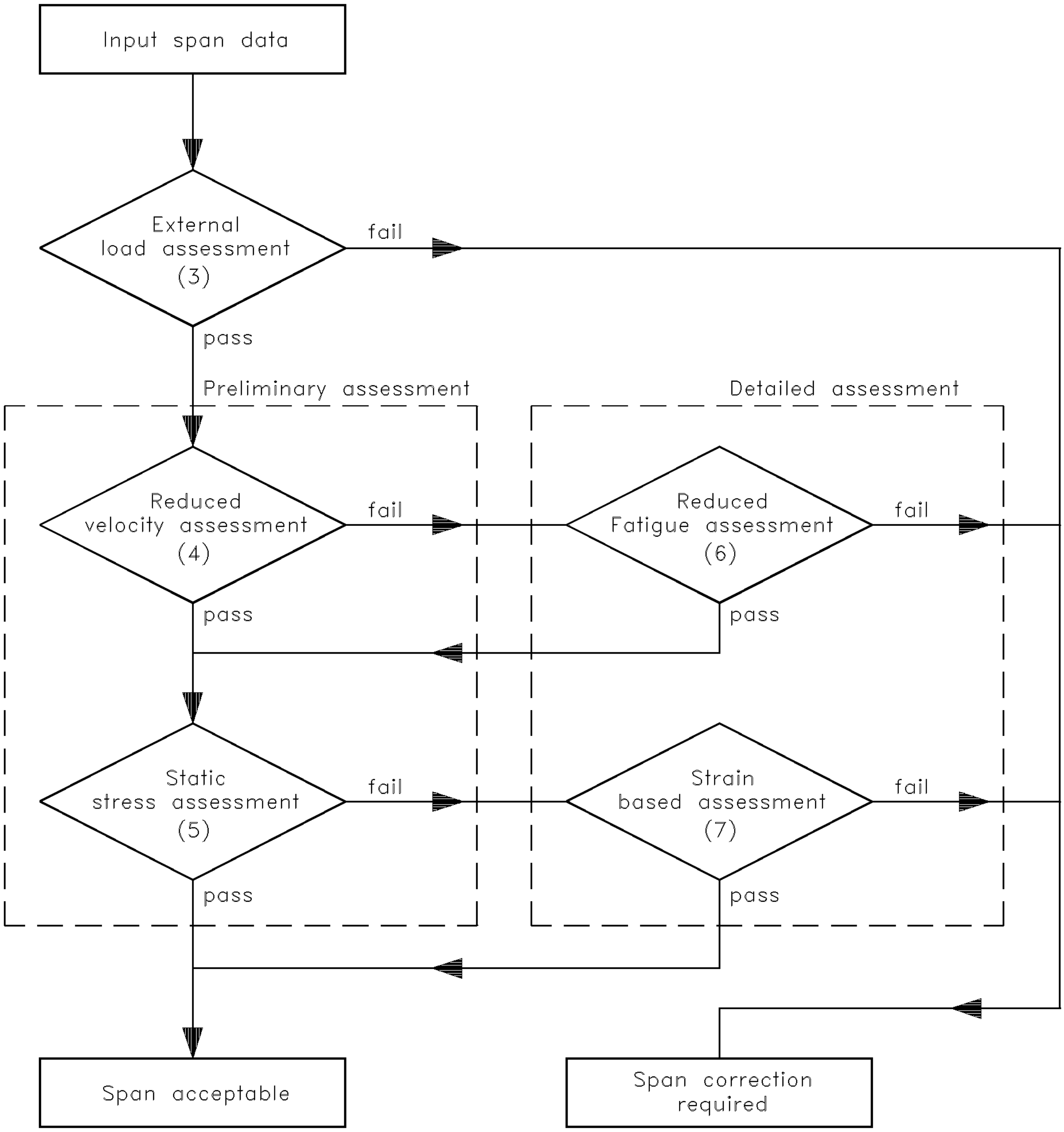


FIGURE 2 SIMPLE FIXED - PINNED SPAN MODEL

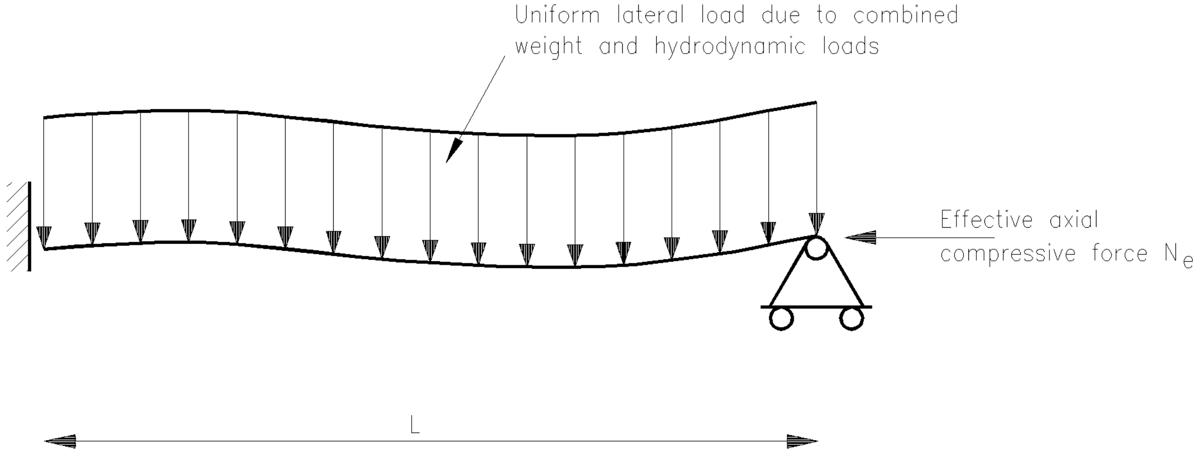
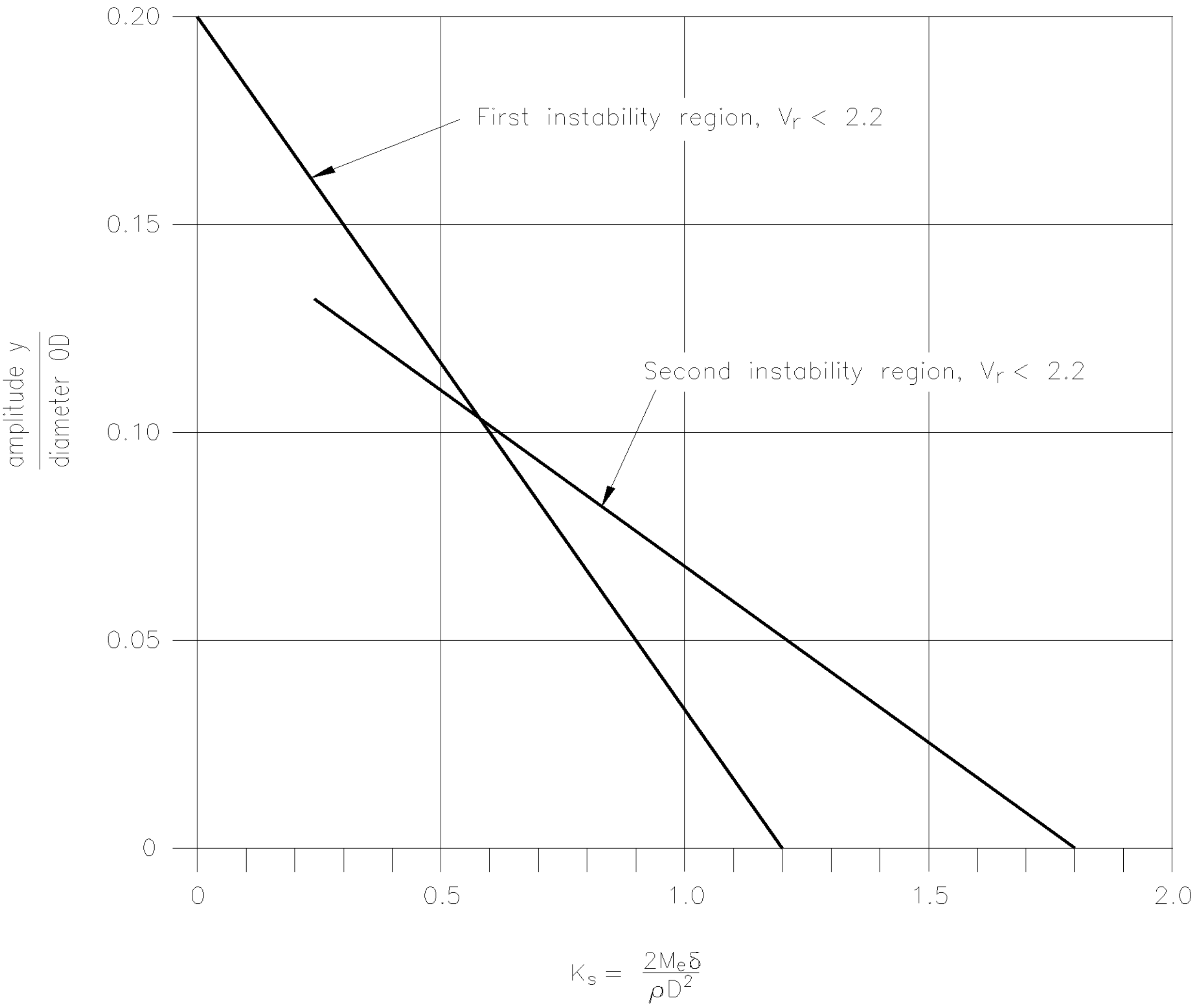


FIGURE 3 AMPLITUDE OF IN-LINE MOTION AS A FUNCTION OF K_s



APPENDIX A WORKED EXAMPLE

A.1 SCOPE

This worked example illustrates the application of DEP 31.40.10.15-Gen. All equation and section references in this worked example relate to that document unless indicated otherwise.

A.2 INPUT DATA

A.2.1 General pipeline data

The worked example is for a span of 30 metres length in a 20" pipeline carrying oil, in the Central North Sea.

The span is modelled as a beam-column with fixed-pinned boundary conditions, subject to axial load and uniform lateral loads along the length of the span.

The pipeline is fully axially restrained.

A.2.2 Pipeline and span data

(Table A.1) gives the details of the pipeline under consideration. The table also outlines the parameters defining the span assessed in this worked example.

Table A.1 Data for pipeline and span

Parameter	Units	Value
Pipeline:		
Nominal outside diameter of the steel pipe(OD_{st})	m	0.508
Nominal wall thickness	mm	15.88
Material grade	-	API 5L X60
Young's modulus (E)	Mpa	2.07×10^5
Poisson ratio (ν)	-	0.3
Steel density	kg/m^3	7850
Coefficient of thermal expansion (α)	C^{-1}	11.6×10^{-6}
External corrosion coating	-	Asphalt enamel
Corrosion coat thickness	m	0.0065
Corrosion coat density	kg/m^3	1300
Concrete coating thickness	m	0.1
Concrete coating density	kg/m^3	3000
Thickness of marine growth	m	0
Internal diameter (ID)	m	0.4762
Outside diameter of pipeline including coating(s) (OD)	m	0.721
Design life	years	20
Span:		
Span length (L)	m	30
Water depth	m	91.5
Gap under central part of span as a fraction of the overall outside diameter(G/OD)		0.277
Logarithmic decrement of damping of the span in air (δ)		0.126
Bearing of pipeline	degrees	150

A.2.3 Operating and environmental data for fatigue assessment

(Table A.2) gives the (significant) environmental data and normal pipeline operating conditions required for fatigue assessment of the span.

Table A.2 Data for fatigue assessment

Parameter	Units	Value
Environmental:		
Density of sea-water (ρ)	kg/m^3	1025
Temperature of sea-water during installation	°C	4
Maximum steady current	m/s	0.59
Steady current reference height	m	top of pipe
Significant wave height	m	12.8
Significant wave period (T_s)	s	12.1
Content:		
Fluid		Oil
Contents density	kg/m^3	870
Normal operating temperature	°C	25
Normal operating contents pressure (P_i)	bar	120

A.2.4 Data for stress assessment

(Table A.3) contains the (maximum) environmental conditions and extreme operating conditions to be used for the stress assessment.

Table A.3 Data for stress analysis

Parameters	Units	Value
Environmental:		
Maximum wave height	m	23.8
Maximum wave period	s	17.1
Content:		
Extreme operating temperature	°C	30
Extreme operating pressure (P_i)	bar	134

A.3 EXTERNAL LOAD ASSESSMENT (SECTION 3)

For the purposes of this example, external loads are not considered. It is assumed that a separate analysis has demonstrated that the span can withstand loads from trawlgear present in the area.

A.4 REDUCED VELOCITY ASSESSMENT (SECTION 4)

The preliminary assessment of VIV is carried out in accordance with (section 4).

A.4.1 Axial load on the span

The effective axial compressive force in a fully restrained pipeline is given by (equation 2.1) for the normal operating conditions given in (Table A.2). If the residual installation tension is conservatively ignored, then the resulting effective axial compressive force is 2.09×10^6 N.

A.4.2 Natural frequency of span

The first natural frequency of a beam-column subjected to an axial compressive force is given by (equation 4.3). For a fixed-pinned span, the frequency factor and Euler constant are 15.4 and 2.05 respectively. This equation can therefore be rewritten using the data in (Table A.1) and the effective axial compressive force as calculated in (A.4.1) to give a first natural frequency of 0.575 Hz.

A.4.3 Wave and current velocity

The peak wave velocity is calculated from linear wave theory. Based on the significant wave data in (Table A.2), the peak wave-induced velocity perpendicular to the pipe at the top of the pipeline is 0.52 m/s. The current velocity perpendicular to the pipe at the top of the pipeline is given as 0.59 m/s.

A.4.4 Limiting criteria for vortex-induced vibration

Fatigue damage will not occur if the reduced velocity given by (equation 4.1) is less than 1.0. In this example, the Keulegan-Carpenter number, as given by (equation 4.2), is 8.7 and so the contribution of the wave-induced current to (equation 4.1) may be ignored. This gives a reduced velocity of 1.4. Fatigue damage may not therefore be ignored.

Cross-flow VIV may be safely ignored if the reduced velocity given by (equation 4.6) is less than 3.0. The Keulegan-Carpenter number indicates that the contribution of the wave-induced current to (equation 4.6) may not now be ignored, and so the reduced velocity is 2.7. Occurrence of cross-flow VIV is therefore unlikely.

The possibility of in-line VIV can be ignored if either (equation 4.4) or (equation 4.5) is satisfied. For this example, the gap under the span as a fraction of overall outside diameter is 0.277, therefore (equation 4.4) is not satisfied. In addition, the stability parameter is calculated to be 0.644, so (equation 4.5) is not satisfied. Based on the above results, a detailed assessment of in-line VIV is necessary before it can be concluded whether the span is acceptable.

A.5 FATIGUE ASSESSMENT (SECTION 6)

A.5.1 Conditions for permitting flow-induced vibrations (6.1.1)

Cross-flow VIV is not permitted. However, the span has already been shown (A.4.4) to be unlikely to suffer damage from cross-flow VIV. Also, there are no connectors or other fittings in the vicinity of the span where intensification of the fluctuating bending stress may occur. In-line VIV may therefore be permitted provided it is demonstrated that the fatigue damage does not exceed 0.1 during the lifetime of the pipeline.

A.5.2 Span response from in-line VIV (6.1.2)

In-line VIV should be taken into account only if the criteria laid down by (equation 6.1), (equation 6.2) and (equation 6.3) are satisfied simultaneously. All three of these conditions are satisfied, see (A.4.4), and in-line VIV must therefore be assessed.

A.5.3 Fatigue assessment (6.1.4)

Proprietary software has been used to determine the fatigue loading on the pipeline span.

Wave and current scatter data are first used to generate a large number of environmental load cases experienced by the pipeline over one year, together with their probability of occurrence. The wave and current scatter data provide the relative number of occurrences of wave height and current velocity for different compass directions.

The analysis assumes that fatigue damage caused by vortex-induced vibrations is independent of that caused by wave-induced vibrations.

For VIV, the span reduced velocity is calculated in the combined steady current and instantaneous wave velocity. From this, the oscillation amplitudes due to VIV are determined by interpolation of experimental results from full-scale pipeline tests. The maximum bending stresses are then calculated using a fixed-pinned beam-column model. The fatigue damage for each load case can then be determined from appropriate S-N fatigue curve data.

For wave-induced vibrations, the maximum hydrodynamic forces on the span due to oscillatory wave loading are first found. From this the maximum bending stresses are calculated and the fatigue damage is found from appropriate S-N curve data.

The annual fatigue damage for each load case is then found by weighting the number of vibration cycles per year by the probability of that load case occurring and dividing the result by the calculated number of cycles to failure. The total fatigue damage is the sum of the annual damage resulting from each load case multiplied by the design life of the pipeline.

A.5.4 Results

The required input and output for the program used for this example is given in (A.9).

The annual fatigue damage has been calculated to be 0.00094 per year and the total fatigue damage over the 20 years design life is then 0.019, assuming no initial damage.

The allowable fatigue damage limit is 0.1 (6.1.4) and the span therefore passes the criteria for fatigue assessment.

A.6 STATIC STRESS ASSESSMENT (SECTION 5)

A.6.1 Wave and current velocity

The peak wave velocity is calculated from linear wave theory. Based on the maximum wave data in (Table A.3), the peak wave-induced velocity perpendicular to the pipe at the top of the pipeline is 2.25 m/s.

The current velocity perpendicular to the pipe at the top of the pipeline is 0.59 m/s.

The Keulegan-Carpenter number, as given by (equation 4.2) with the wave and current velocities for the maximum wave, is therefore 53.4. The Keulegan-Carpenter number is used, along with the Reynolds number and the ratio of span height to overall outside diameter, to establish hydrodynamic coefficients from DnV 1981 which give the hydrodynamic forces on the pipeline.

A.6.2 Maximum load on span

The maximum load on the span is the greatest combined loading resulting from its own weight and all hydrodynamic forces throughout the 360° wave cycle. The hydrodynamic loads can be calculated according to DnV 1981. The force per unit length resulting from the combined submerged weight and hydrodynamic loads on the span is found to be 5620 N/m.

A.6.3 Axial load on the span

The effective axial compressive force is calculated using (equation 2.1) applying the conditions for the extreme load case given in (Table A.3). If the residual tension is conservatively ignored, then the resulting effective axial compressive force is 2.49×10^6 N.

A.6.4 Static stress assessment

A.6.4.1 Maximum bending moment

The maximum bending moment is calculated using the formula for a pinned-fixed beam given in (section 5). The maximum bending moment is equal to 1.66×10^6 Nm.

A.6.4.2 Maximum/minimum bending stress

The maximum bending stress is calculated from the bending moment and is 568 MPa. The bending stress is tensile at the top of the pipe (12 o'clock position) and compressive at the bottom (6 o'clock position).

A.6.4.3 Axial stress

The mean axial stress is calculated according to DEP 31.40.00.10-Gen. (Appendix 2), using the mean diameter of the steel pipe. The residual tension, sag-induced tension and feed-in are ignored in this example. The mean axial stress is –4.6 MPa.

A.6.4.4 Hoop stress

The mean hoop stress is calculated according to DEP 31.40.00.10-Gen. (Appendix 2), using the mean diameter of the steel pipe. The hoop stress is 193 MPa.

A.6.4.5 Span assessment

The maximum von Mises stress is calculated according to DEP 31.40.00.10-Gen. (Appendix 2) to be 690 MPa. The span is considered safe if the maximum von Mises stress is less than 90% of the specified minimum yield strength for the steel. The 90% SMYS limit for this pipeline steel is 373 MPa, which is exceeded by the maximum von Mises stress. The span therefore fails the preliminary static stress assessment. It is necessary to perform a strain-based assessment in order to further assess whether the span is acceptable.

A.6.4.6. Stress Program

The input and output of a program for stress calculations is shown in A.10.

A.7 STRAIN-BASED ASSESSMENT (SECTION 7)

A.7.1 Finite element model

A pipeline deformation beyond yield analysis is normally carried out numerically.

A finite-element model of the span is produced using a general purpose non-linear finite-element program. In order to model axial feed-in to the pipeline span, a 6.0 km long model is considered. Symmetry about the span mid-point allows a half-model of 3.0 km to be used.

The model is constructed using elasto-plastic and elastic pipe elements to model the pipe, and non-linear spring elements to model the seabed axial friction. Elasto-plastic elements are used for the first 100 m of the model, with elastic elements used along the remainder of the model where no plasticity is expected. The pipe is restrained vertically along the model from a distance of 50 m from the span. Along the initial 50 m the vertical seabed soil stiffness is modelled as a spring with stiffness $1x10^8$ N/m: free vertical movement is allowed upwards but movement into the seabed is resisted by the springs. The element spacing along the model is such that there are very short elements for the first 100 m and progressively larger elements away from the span. The finite element model is shown in (Figure A.1).

A.7.2 Scope of numerical analysis

The numerical analysis is performed in four stages:

1. The pipe is loaded up from initial conditions (hydrostatic pressure, ambient temperature, own weight and no displacement) to its normal operating condition by the application of operating pressure and then operating temperature. This gives the stresses in the pipe under own weight and normal operating conditions.
2. The pressure and temperature are increased from the normal operating condition assessed in stage 1 to the extreme operating condition by increasing the pressure and then the temperature to the extreme values. This provides an assessment of the extreme static stresses and total strains.
3. Strain-based assessment is permitted if it can be demonstrated that displacement is constrained before unacceptable strains occur. The temperature of the pipe is therefore increased until the span touches down and the corresponding strains are checked. In addition, the application of a strain-based assessment assumes that ratcheting does not occur under cyclic loading. A pressure-temperature cycle is therefore analysed.
4. Environmental loading is applied in the form of extreme horizontal loading resulting from the worst combination of steady current and wave induced velocity, for the pipe under the normal operating condition assessed in stage 1. The results indicate whether plastic deformation is likely to occur as a result of maximum environmental load.

A.7.3 Result

A.7.3.1 Normal operating conditions

The deflection and stress under normal operating pressure and temperature are determined. These are shown in (Figure A.2) and (Figure A.3). It is assumed that the span was inspected under normal operating conditions. The gap under the span in these conditions is therefore taken to be 0.2 m. It is seen that the maximum von Mises stress is 333 MPa (80% of SMYS) and the span is therefore acceptable under normal operating conditions.

A.7.3.2 Extreme Loading Analysis

The second stage of the analysis is to load the span from normal operating conditions up to the extreme pressure and temperature (by first increasing the pressure and then the temperature). The resulting deformations and stresses are also shown in (Figure A.2) and (Figure A.3). It is seen that the maximum von Mises stress rises to 394 MPa (95% of SMYS). The maximum strain in the pipe wall under these conditions is 0.197%, with a corresponding ovalisation of 1.013%. The span deflects by an additional 0.10 m, indicating that it will not touch down under extreme pressure and temperature.

A.7.3.3 Strain-based analysis

In order to check that span deflection will be constrained before strains exceed acceptable values, the temperature of the pipe is increased until the span touches down. The maximum von Mises stress at touch-down is 397 MPa (96% of SMYS).

To be acceptable the span has to satisfy the following criteria at maximum displacement:

1. The maximum strain in the span shall be less than 0.5% to avoid fracture. The maximum strain in the pipe when the spans touches the seabed is 0.24%, therefore the strain criterion for the prevention of pipeline fracture is satisfied.
2. The compressive strain in the span shall be less than that required to cause wrinkling or buckling of the pipe.

   The critical compressive bending strain causing local buckling is a function of the diameter-to-wall-thickness ratio of the steel pipe. From Annex C of BS 8010-3, the critical compressive bending strain is 1.5%. The maximum compressive strain is 0.24% so this criterion is also satisfied.
3. Pipe ovalisation shall not exceed 2.5%.

   The ovalisation of a pipeline due to bending and external pressure can be calculated using Annex C of BS 8010-3. If the initial ovalisation is assumed to be 1.0%, the ovalisation of the pipe at 0.24% strain is 1.12%. The ovalisation criterion is therefore also satisfied.

To assess the significance of ratcheting, the span is analysed for three load cycles from hydrostatic pressure and ambient temperature up to extreme pressure and temperature and then back down again. The stress history at the mid-point of the span is shown in (Figure A.4). The maximum equivalent stress is reduced from 394 MPa to 388 MPa between the first and second cycle, providing evidence of the small plastic strain introduced when the span is first loaded. There is no change in the equivalent stresses during subsequent load cycles, indicating that ratcheting is not occurring, and the span is safe even under extreme pressure and temperature load cycles.

The maximum strains in the pipe are within acceptable limits and ratcheting does not occur under cyclic loading. The span is therefore acceptable even under the loading imposed by extreme operating conditions.

A.7.3.4 Environmental loading

A uniformly distributed horizontal load is applied to the pipeline to assess the effects of environmental loading. (Figure A.5) shows the variation of von Mises stress along the 9 o'clock position on the pipe. Horizontal displacement of the pipeline in this condition results in an increase in tension, and therefore reduces the maximum equivalent stress, which is compressive. The maximum equivalent stress is reduced to 222 MPa (54% of SMYS). The span is therefore acceptable under environmental loading.

A.8 CONCLUSION

The example span fails the initial stress based analysis, and it also fails the reduced velocity check with regard to in-line VIV.

However, a detailed fatigue analysis of VIV finds that the induced fatigue damage is within acceptable limits for the design life of the pipeline. A finite analysis of the yield behaviour of the span reveals that the maximum strain is within allowable limits and ratcheting does not occur.

The span is therefore found to be acceptable.

A.9 PROGRAM INPUT/OUTPUT FOR CALCULATION OF FATIGUE DAMAGE

<u>Pipeline Data</u>

Outside diameter	(m)	.508
Wall thickness	(m)	.01588
Steel density	(kg/m^3)	7850
Young's modulus	(N/m^2)	2.07E+11
SMYS	(N/m^2)	4.14E+08
Poisson's ratio	(-)	.3
Thermal expansion coefficient	(°C $^{-1}$)	.0000116
Thickness of coating	(m)	.0065
Density of coating 1	(kg/m^3)	1300
Thickness of coating	(m)	0
Density of coating 2	(kg/m^3)	0
Thickness of coating	(m)	0
Density of coating 3	(kg/m^3)	0
Thickness of coating	(m)	0
Density of coating 4	(kg/m^3)	0
Thickness of concrete coating	(m)	.1
Density of concrete coating	(kg/m^3)	3000
Thickness of marine growth	(m)	0
Density of marine growth	(kg/m^3)	0

<u>Operational data</u>

Contents density	(kg/m^3)	870
Contents temperature	(°C)	25
Contents pressure	(bar)	120

<u>Environmental data</u>

Water depth	(m)	91.5
Density of sea water	(kg/m^3)	1025
Ambient temperature of sea water	(°C)	4
Maximum steady current	(m/s)	.59
Steady current reference height	(m)	.915
Maximum wave height	(m)	12.8
Maximum wave period	(s)	12.1
Seabed roughness	(m)	.00002
Wave scatter filename	(-)	wave.dat
Storm current scatter filename	(-)	storm.dat
Tidal current scatter filename	(-)	tidal.dat
JONSWAP Peakedness parameter	(-)	3.3
Pipeline bearing	(°)	150

<u>S-N curve data</u>

S-N curve gradient	(N/m^2)	-.333
S-N curve minimum stress limit	(N/m^2)	0
S-N curve intercept	(N/m^2)	7.586E+09

<u>Calculation options</u>

Stress safety factor	(-)	.9
Strain safety factor	(-)	1
Fatigue safety factor	(-)	1
Hydrodynamic force coefficients (DNV76,DNV81)	(-)	DNV81
Current boundary layer profile (LOG,1/7,1/10,EXPL)	(-)	LOG

Extreme wave theory (STOKES5,AIRY)	(-)	AIRY
Fatigue VIV data (HR,DNV81)	(-)	DNV81
Full axial restraint (YES,NO)	(-)	YES
Residual tension (axial restraint = YES)	(N)	0
Span dynamic damping ratio	(-)	.02

Span data

Natural frequency	(Hz)	0
Smallest span length	(m)	30
Largest span length	(m)	30
Span length increment	(m)	2
Gap below the span	(m)	.2

Pipe properties

Overall diameter	(m)	0.721E+00
Submerged weight	(N/m)	0.518E+04
Dry weight	(N/m)	0.928E+04
Effective mass	(kg/m)	0.137E+04
Axial stiffness	(N)	0.508E+10
Flexural rigidity	(Nm^2)	0.154E+09
Stability parameter	(-)	0.644E+00

Pipe forces

Effective axial force	(N)	0.209E+07
Extreme wave-induced velocity	(m/s)	0.524E+00
Extreme steady current velocity averaged over pipe	(m/s)	0.559E+00
Extreme steady current velocity at top of pipe	(m/s)	0.590E+00
Reynolds number	(-)	0.517E+06
Keulegan-Carpenter number	(-)	0.879E+01
Drag coefficient	(-)	0.173E+01
Inertia coefficient	(-)	0.235E+01
Lift coefficient	(-)	0.767E+00
Maximum force on span	(N/m)	0.518E+04
Ratio of maximum force to submerged weight	(-)	1.000

Fatigue Analysis

Span Length (m)	Natural frequency (Hz)	Fatigue damage in one year (no safety factor) Wave	Vortex	Total	Maximum reduced velocity	Maximum bending stress Vortex (N/m^2)	Wave (N/m^2)	Fatigue life (years)
30.0	0.575E+00	0.206E-03	0.735E-03	0.941E-03	0.269E+01	0.607E+08	0.431E+08	0.106E+04

A.10 PROGRAM OUTPUT FOR STRESS AND STRAIN CALCULATIONS

Pipeline Data

Outside diameter	(m)	.508
Wall thickness	(m)	.01588
Steel density	(kg/m^3)	7850
Young's modulus	(N/m^2)	2.07E+11
SMYS	(N/m^2)	4.14E+08
Poisson's ratio	(-)	.3
Thermal expansion coefficient	(°C $^{-1}$)	.0000116
Thickness of coating	(m)	.0065
Density of coating 1	(kg/m^3)	1300
Thickness of coating	(m)	0
Density of coating 2	(kg/m^3)	0
Thickness of coating	(m)	0
Density of coating 3	(kg/m^3)	0
Thickness of coating	(m)	0
Density of coating 4	(kg/m^3)	0
Thickness of concrete coating	(m)	.1
Density of concrete coating	(kg/m^3)	3000
Thickness of marine growth	(m)	0
Density of marine growth	(kg/m^3)	0

Operational data

Contents density	(kg/m^3)	870
Contents temperature	(°C)	30
Contents pressure	(bar)	134

Environmental data

Water depth	(m)	91.5
Density of sea water	(kg/m^3)	1025
Ambient temperature of sea water	(°C)	4
Maximum steady current	(m/s)	.59
Steady current reference height	(m)	.915
Maximum wave height	(m)	23.8
Maximum wave period	(s)	17.1
Seabed roughness	(m)	.00002
Wave scatter filename	(-)	wave.dat
Storm current scatter filename	(-)	storm.dat
Tidal current scatter filename	(-)	tidal.dat
JONSWAP Peakedness parameter	(-)	3.3
Pipeline bearing	(°)	150

Calculation options

Stress safety factor	(-)	.9
Strain safety factor	(-)	1
Fatigue safety factor	(-)	1
Hydrodynamic force coefficients (DNV76,DNV81)	(-)	DNV81
Current boundary layer profile (LOG,1/7,1/10,EXPL)	(-)	LOG
Extreme wave theory (STOKES5,AIRY)	(-)	AIRY
Fatigue VIV data (HR,DNV81)	(-)	DNV81
Full axial restraint (YES,NO)	(-)	YES
Residual tension (axial restraint = YES)	(N)	0
Span dynamic damping ratio	(-)	.02

Span data

Natural frequency	(Hz)	0
Smallest span length	(m)	30
Largest span length	(m)	30
Span length increment	(m)	2
Gap below the span	(m)	.2

Pipe properties

Overall diameter	(m)	0.721E+00
Submerged weight	(N/m)	0.518E+04
Dry weight	(N/m)	0.928E+04
Effective mass	(kg/m)	0.137E+04

Axial stiffness	(N)	0.508E+10
Flexural rigidity	(Nm^2)	0.154E+09
Stability parameter	(-)	0.644E+00

Pipe forces

Effective axial force	(N)	0.249E+07
Extreme wave-induced velocity	(m/s)	0.225E+01
Extreme steady current velocity averaged over pipe	(m/s)	0.559E+00
Extreme steady current velocity at top of pipe	(m/s)	0.590E+00
Reynolds number	(-)	0.134E+07
Keulegan-Carpenter number	(-)	0.534E+02
Drag coefficient	(-)	0.117E+01
Inertia coefficient	(-)	0.235E+01
Lift coefficient	(-)	0.271E+00
Maximum force on span	(N/m)	0.562E+04
Ratio of maximum force to submerged weight	(-)	1.084

Extreme Loading Analysis

Span Length (m)	Effective axial force (N)	Wall axial force (N)	Mean axial stress (N/m^2)	Maximum bending moment (Nm)	Maximum bending stress (N/m^2)	Maximum von Mises stress (N/m^2)	Central deflection (m)	Maximum possible strain (N/m^2)
30.0	0.249E+07	-.114E+06	-.463E+07	0.166E+07	0.568E+09	0.690E+09	0.108E+00	0.267E+00

FIGURE A.1 SIMPLE DIAGRAM OF FINITE ELEMENT MODEL

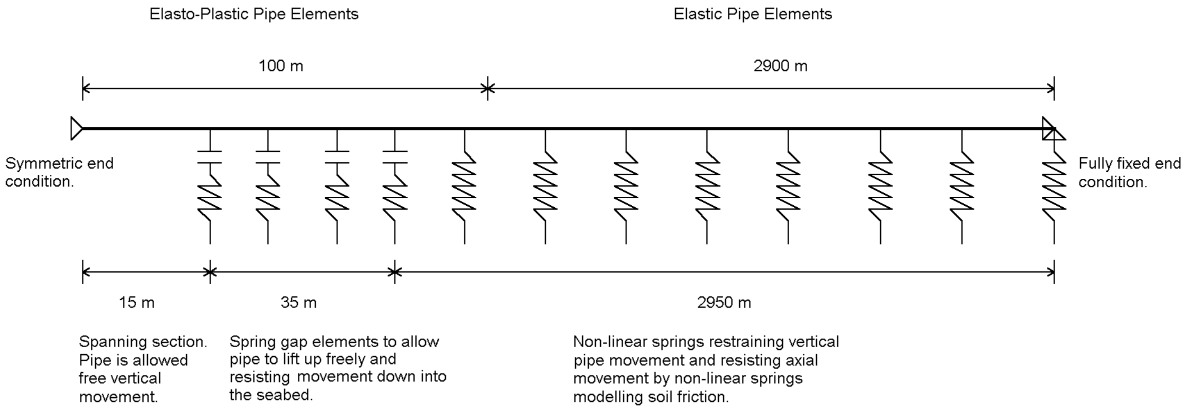


FIGURE A.2 DISPLACED SHAPE OF PIPELINE UNDER NORMAL AND EXTREME OPERATING CONDITIONS

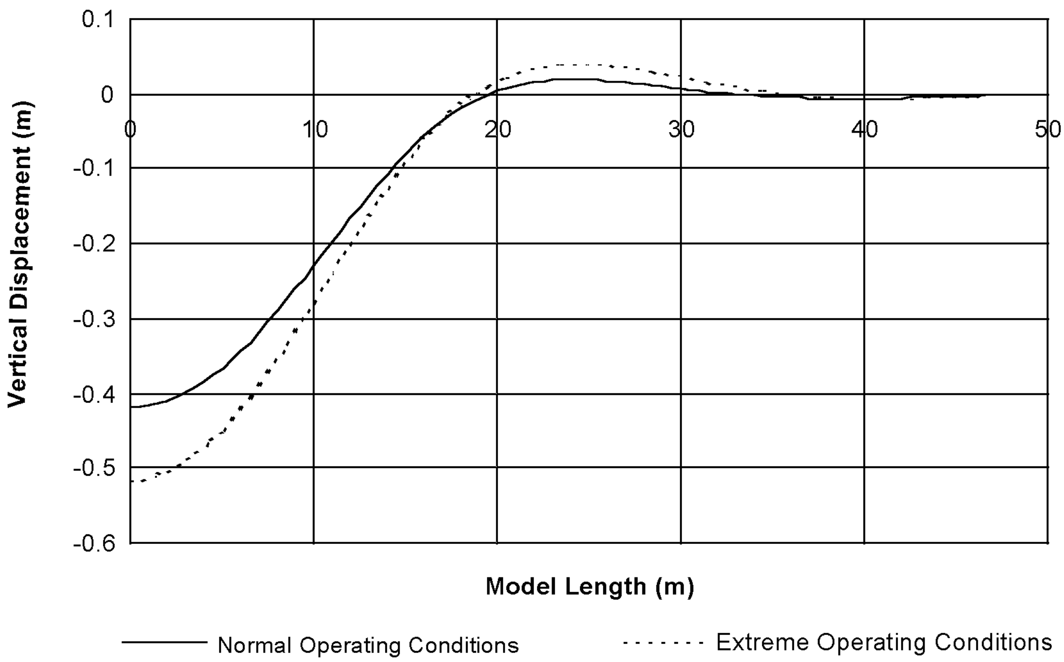


FIGURE A.3 MAXIMUM EQUIVALENT STRESS UNDER NORMAL AND EXTREME OPERATING CONDITIONS

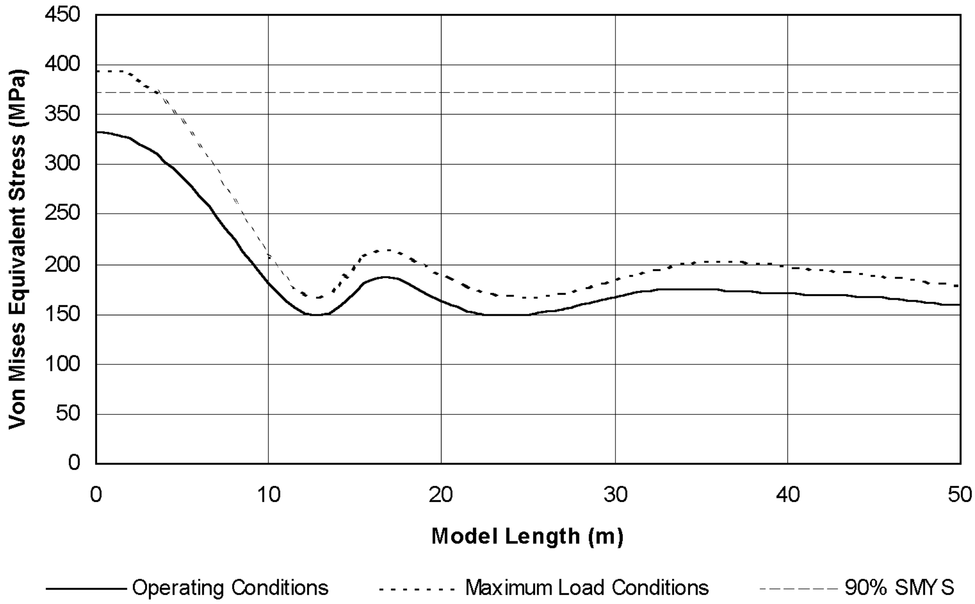


FIGURE A.4 MAXIMUM EQUIVALENT STRESS HISTORY AT SPAN MID-POINT FOR THREE LOAD CYCLES

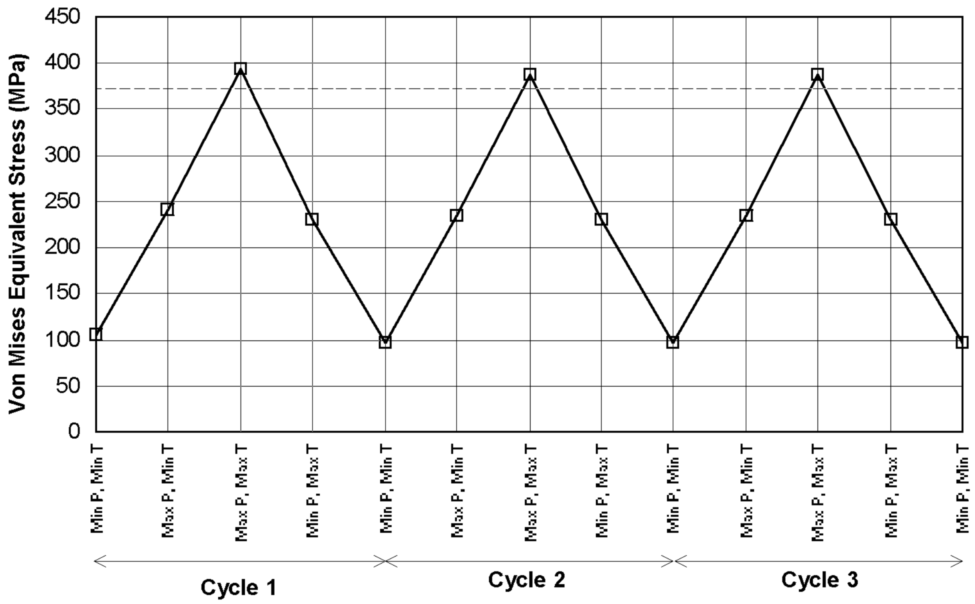


FIGURE A.5 MAXIMUM EQUIVALENT STRESS AT 9 O'CLOCK POSITION UNDER ENVIRONMENTAL LOADING