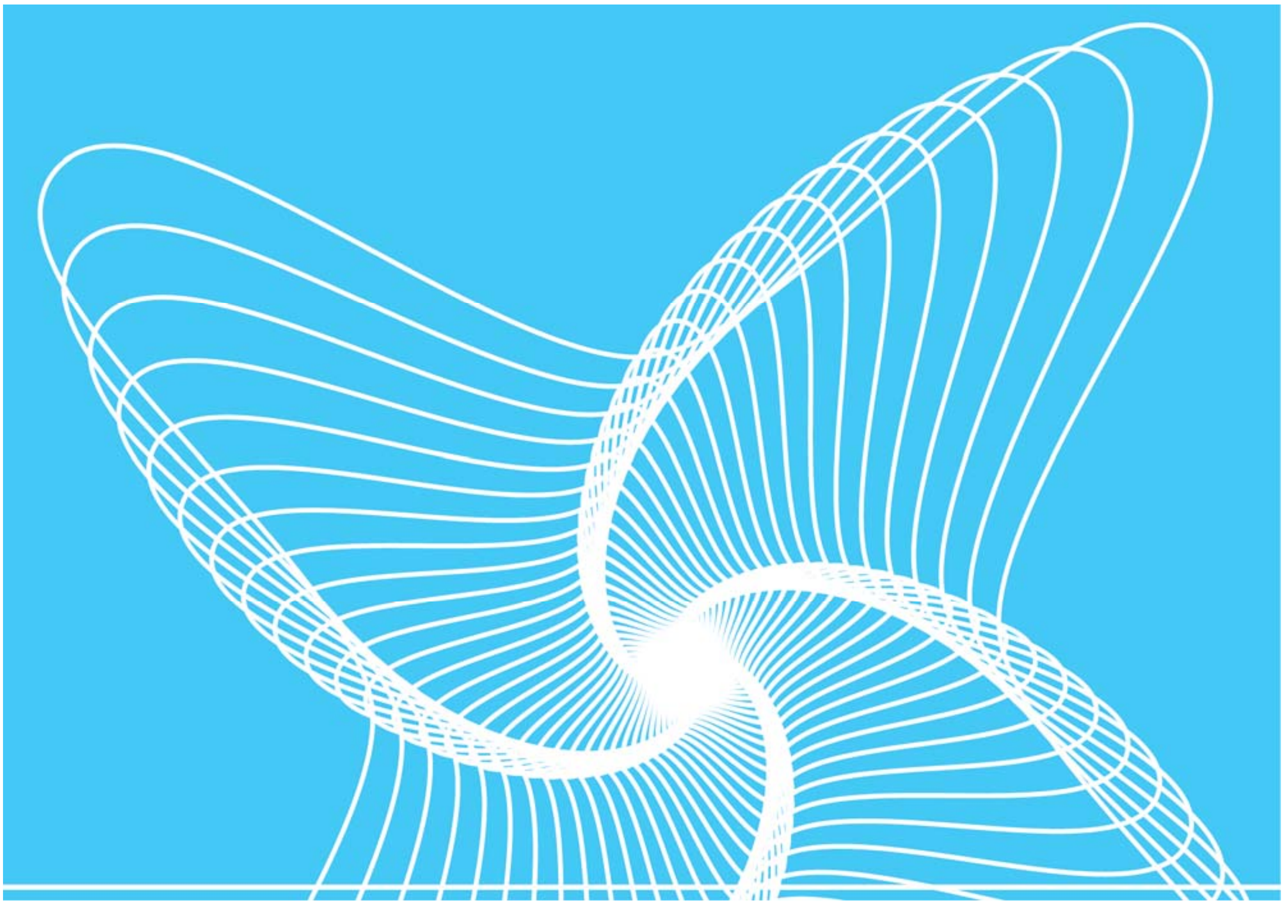
SESAM WHITE PAPER

# HELICA

## Cross section analysis of compliant structures – flexibles, umbilicals and cables



**SAFER, SMARTER, GREENER**

Reference to part of this report which may lead to misinterpretation is not permissible.

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Date: June/2016

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# 1 SUMMARY

Fatigue analysis of umbilical components such as helix tensile armors and steel tubes are critical design issues for dynamic umbilicals and flexible pipes. The basis for assessment of fatigue damage of such elements is the long-term stress cycle distribution at critical locations on the helix elements caused by long-term environmental loading on the system. The long-term stress cycle distribution will hence require global dynamic time domain analysis followed by a detailed cross-sectional analysis in a large number of irregular sea states.

An overall computational consistent and efficient fatigue analysis scheme is outlined in this paper. A description is given of the cross-sectional analysis technique required for fatigue stress calculation with particular attention to the helix elements. The global cross section is exposed to pure bending, tensile, torsion and pressure loading. The state of the different cross section elements are based on the global response. Special emphasis is placed on assessment of friction stresses caused by the stick−slip behavior of helix elements in bending. Such effects are known to be of special importance for fatigue life assessments of deepwater flexible pipes and umbilicals due to increased contact pressure between the individual elements in the cross-section.

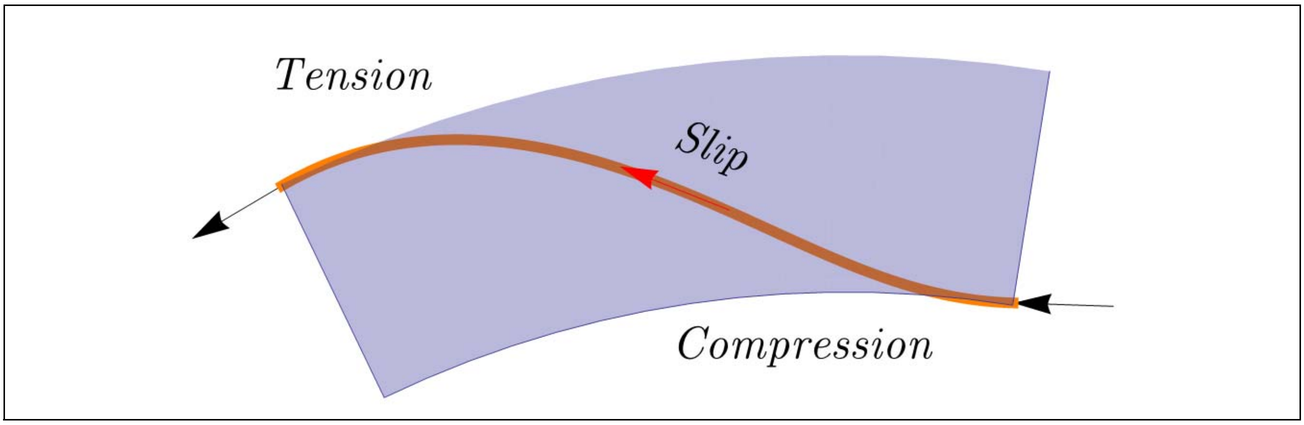
The described cross-sectional analysis techniques are based on an extensive literature survey and are hence considered to represent industry consensus.

# 2 COMPLIANT STRUCTURES AND CROSS SECTION ANALYSIS

Compliant structures has proved to be an essential technology for oil exploration outside the Norwegian coast. Floating structures experience large wave induced vertical motions. The connecting pipes needs to be both flexible and have suffucent strength to withstand the change in geometry caused by large floater motions. The required bending flexibility of risers and umbilicals is achieved by arranging strength- and functional elements in a helix geometry. The helix geometry allows the elements to slip in order to release axial stresses built up by cross-sectional bending. This mechanism is essential for arranging flexible risers and umbilicals in compliant configurations that are capable of absorbing loads due to floater motions in harsh environmental conditions.

The penalty is, however that assessment of fatigue stresses in helix elements becomes complex due to the stick − slip behavior of helix elements in bending, illustrated in Figure 2-1.

**Figure 2-1 Slip of helix elements in bending.**




The purpose of fatigue analysis is assessment of fatigue damage in all relevant elements in the cross-section for a long-term dynamic loading environment. Fatigue analysis of helix elements such as tensile armors and steel tubes are critical design issues for umbilicals and flexible pipes. Critical areas are normally at the floater interface where bend limiting devices, i.e. a bend stiffener or a bellmouth, are applied to avoid overbending in extreme load situations and reduce long-term fatigue loading.

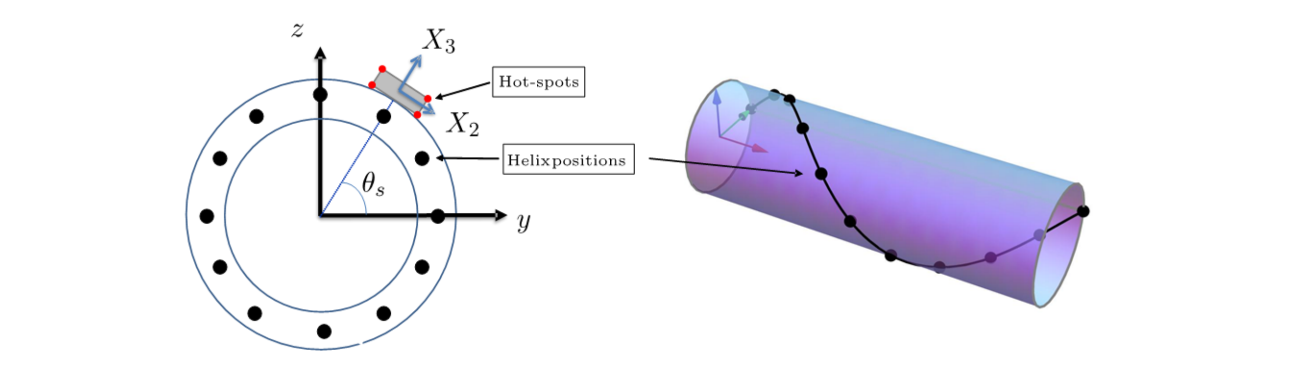
ISO 13628-5 – Subsea umbilicals is the main reference for design and load-effect analysis of umbilicals. This standard requires that fatigue life shall be calculated considering all relevant cyclic loading imposed on the umbilical over its design life. The most onerous fatigue loading for umbilicals in dynamic service are normally:

- Wave induced fatigue loading due to direct wave loading and associated floater motions
- Vortex Induced Vibration (VIV) in steady current conditions.

Both loading scenarios will require fatigue damage calculations in numerous short-term conditions to represent the long-term fatigue loading environment. As an example, wave induced fatigue analyses will typically require stress calculation in about 100−300 stationary irregular sea states each with duration of one hour. In addition, an iterative analysis scheme is in general required for consistent assessment of fatigue damage caused by VIV due to the highly nonlinear stick−slip damping mechanism in bending.

The basis for assessment of fatigue damage in helix elements is the long-term cycle distribution in several hot-spots, i.e. critical positions on the helix cross-section, for a representative number of helix positions, i.e. positions along the helix in one pitch, as shown in Figure 2-2.

**Figure 2-2 Hot-spots and helix positions for fatigue analysis**




The main challenge is hence to establish an overall manageable computational scheme to establish fatigue life estimates with sufficient condence. A computational efficient cross-sectional analysis strategy is hence a vital part of the overall fatigue analysis approach. DNV GL has developed a dedicated computer program named **Helica** to address these design and analysis challenges, /3/ and /4/. The main capabilities are:

- Applicable to umbilicals, power cables, exible risers and similar unbonded structures.
- Load sharing analysis for combined loading.
- Calculation of cross sectional stiffness properties: axial, bending and torsion.
- Fatigue stress analysis of helix elements considering stick−slip behavior in bending.
- Calculation of consistent fatigue stresses by direct application of global response time series as external loading.
- Calculation of capacity curves for the entire cross-section in compliance with applicable design codes.
- Short-term fatigue life and long-term fatigue analysis capabilities.
- Efficient and robust analysis scheme.
- Well documented transparent theoretical formulation representing industry consensus.

One of the main drivers behind this development has been to establish an efficient and consistent fatigue analysis scheme. The main focus of this paper is to give a detailed description of the cross-sectional response models applied to achieve an efficient and robust analysis scheme.

# 3 LOAD SHARING ANALYSIS

## 3.1 General

The computational model is based on an essential 2D formulation allowing for cross-sectional modeling of composite tubes containing helix elements in an unbonded structure. 2D is here to be understood as an average description where the averaging is applied in longitudinal pipe direction. The consequence of this is that possible 3D effects close to terminations can not be handled. The helix elements are assumed to be arranged in well defined layers allowing for treating each helix layer by means of an equivalent tube model with stiffness properties assembled from the individual helix elements. Different types of helix elements may be applied in same layer to model e.g. umbilicals. Different distance from the cross-sectional centerline may also be specified for the individual elements in the same layer. All elements are assumed to have linear elastic material properties.

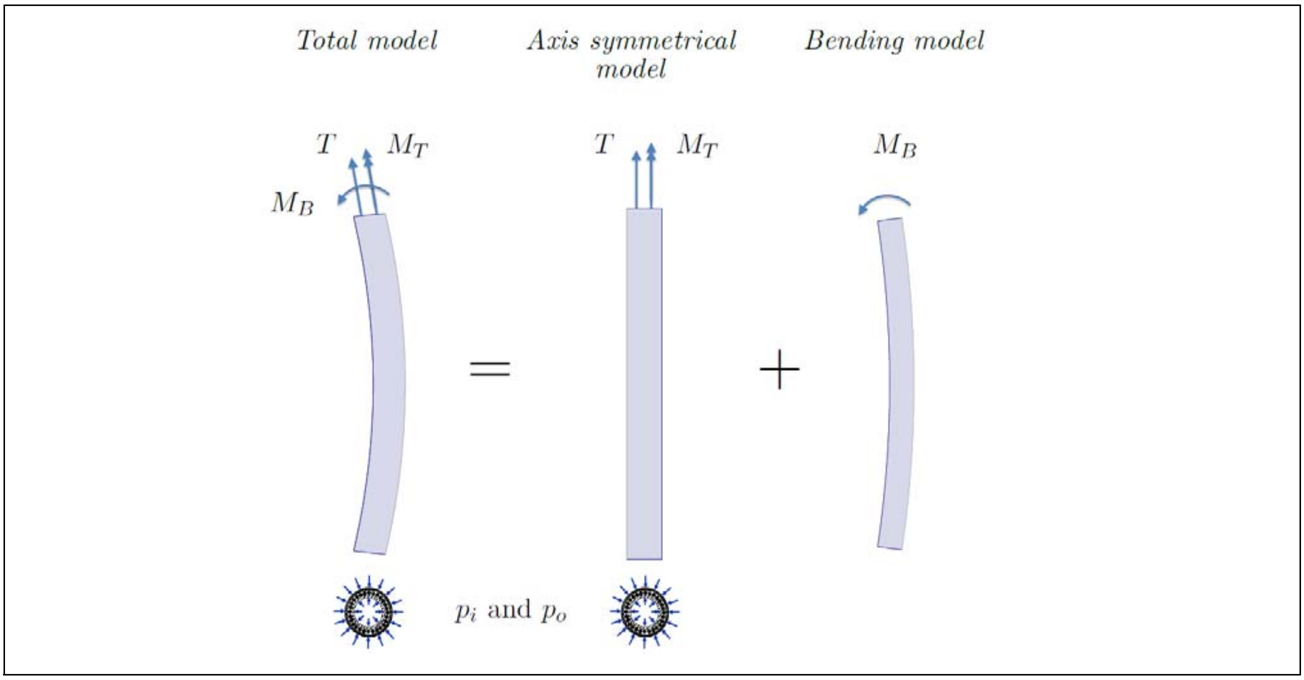
## 3.2 Response model

The main purpose of the cross-sectional analysis is to predict the stresses in all interior elements for an applied external loading. In order to establish efficient response models for cross-sectional analysis, it is convenient to distinguish between the following load models:

- Axis-symmetric loads due to effective tension, torsion moment, internal and external pressure.
- Pure bending, i.e. constant global cross-section curvature.

Separate response models are established for the different load conditions in order to obtain an overall robust, flexible and computational efficient numerical solution scheme. The load model is illustrated in Figure 3-1.

**Figure 3-1 Response models for cross-sectional analysis**



The main purpose and underlying assumptions for these response models are discussed in the following. The purpose of the axis-symmetric response model is to establish the load sharing between the individual components of the cross-section as well as contact forces between the layers under axis-symmetric loading – effective tension, torsion and hydrostatic pressure loads. This analysis enquirers a full model of the cross-section and needs to solve the overall static equilibrium with due regard to inter-layer contact. Frictional effects are disregarded in the axis-symmetrical response model.

The bending response model is an analytical model for the calculation of stresses in helix elements due to cross-sectional bending. The stick | slip model is based on contact forces established by the axis-symmetrical analysis. A major advantage by the analytical bending model is that bending analysis of the helix elements can be carried out one by one without considering a complete model of the cross-section. This ensures a very flexible and efficient computation scheme. The main assumptions of the analytical bending model can be summarized as:

- Constant interlayer contact pressure found by axis-symmetrical analysis. Additional contact pressure induced by bending itself is neglected.
- Friction/contact between helical elements in same layer is neglected, e.g. possible blocking/locking interlayer behavior can not be modeled explicitly.
- No end effects included, i.e. bending takes place well away from terminations.
- Constant global cross sectional curvature is assumed.
- Axial slip of helix elements is assumed, i.e. loxodromic helix geometry assumed during bending.

## 3.3 Axis-symmetric response model

Axis symmetrical response model is built up of concentric layer to model the entire cross sections. All layers are assumed to have the same axial and torsional deformation while the radial deformation is described separately for all layers. Each layer will hence have 1 or 2 radial degrees of freedom (dof) depending on whether the radial deformation of the layer itself is considered or not. The element types used in modeling and analysis are listed in Table 3-1.

**Table 3-1 Typical elements used in modeling and analysis of axis-symmetrical response.**

| Element type | Assumption |
|---|---|
| Thin cylindrical element | Constant through thickness radial displacements; axial, circumferential and in-plane shear strains; $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\varepsilon_{x\theta}$. |
| Thick cylindrical element | Logarithmic through thickness radial displacements; radial, axial, circumferential and in-plane shear strains; $\varepsilon_{RR}$, $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\varepsilon_{x\theta}$ |
| Core element | Generalized cylinder element where the effect is expressed through and element stiffness metrix; $k_{ij}$ |
| Helix element | Helix element with axial strains only; $\varepsilon_{0ss}$ |
| Helix element | Helix element with axial strains, curvatures and torsional shear strains; $\varepsilon_{xx}$, $\kappa_2$, $\kappa_3$ and $\gamma_s$. |

The cylinder layers are intended for modeling of concentric plastic/metallic sheaths, e.g. inner/outer pressure barrier of flexible pipes and external/interior sheaths of umbilicals. The core element is intended for modeling of resulting stiffness properties of one or several layers. A typical application is modeling of resulting stiffness properties of underlying layers supporting one or several layers of cross wound tensile amours. The helix layers are modeled as equivalent thin cylinder layers in the axis-symmetrical analysis. The equivalent cylinder layer is established by assembling the stiffness contributions from each helix component in the layer. The stiffness matrix of each helix element is derived based on slender beam theory assuming the as-produced nominal helix geometry as initial stress free condition, i.e. a state of no stress. The deformations and stresses of each helix component due to axis-symmetrical loading are hence uniquely described by the global axial, torsional and radial deformation of each layer. Full details of all elements are given in /3/.

The global systems of equations includes the impenetrability constraint associated with the internal contact between the the different layers. Physically, the impenetrability equations allow for gaps to open between the layers, but they are not allowed to deform into each other. In order to support an efficient solution of the linear system of equations subjected to constraints it is convenient to reformulate the problem as an associated Quadratic Programming (QP) problem, a special type of mathematical optimization problem. The advantage of the formulation is that it is widely studied in the literature and a number of well established and robust solution schemes exists; like the *active set* method.

The QP solution scheme will hence yield both contact forces and layer displacements as direct output from the analysis. Layer displacements yield the stresses and strains in all interior elements of the cross section while the layer interface contact forces are crucial input to subsequent bending analysis of the helix elements

The solution strategy proposed in **Helica** is novel and has proved to yield a very versatile an efficient axis-symmetrical solver.

## 3.4 Bending response

The additional stresses due to bending can be derived by assuming that the helix follows a loxodromic curve during cross-sectional bending. This means that the helix remains in its original position on the supporting cylinder surface during bending and that it slips in axial direction. This geometrical assumption has gained consensus in the literature, see references in /1/. Experiments have also been conducted to validate this assumption, see Section 4.2. Based on this geometrical assumption, it is fairly straightforward to establish the stress components during bending. This is further described in /3/.

The main stress components in a helix element during bending are:

- Local bending stress due to bending about local weak/strong axes of the helix.
- Friction stress due to the stick/slip behavior in bending.

# 4 VALIDATION

## 4.1 Axis-symmetric reponse

A number of physical test as been performed on the axis-symmetric load conditions. Extensive validation on the axis-symmetric response solver in Helica has been conducted. Comparison to other published results show very good agreement and correlation. References are given in /1/ and a selection is shown in Table 4-1.

**Table 4-1 Axis-symmetrical analysis results | comparison, Vaz, Sævik and Helica.**

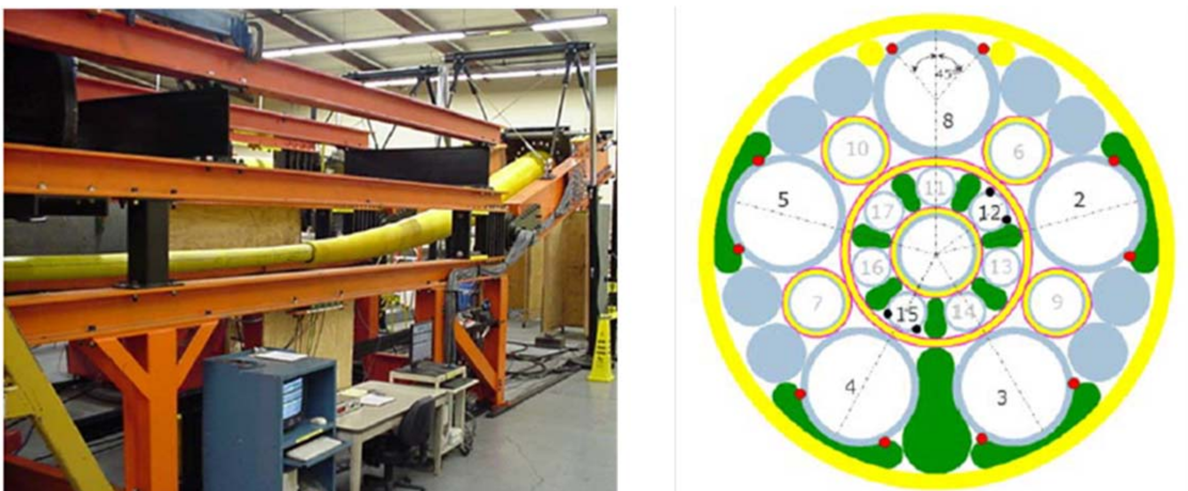
| Feature | Test | Vaz | Sævik | Helica |
|---|---|---|---|---|
| EA under tension, (MN) | $70 - 101$ | $82.9$ | $100$ | $79.5$ |
| Coupling − tension/torsion (m) | | $0.19$ | $0.21$ | $0.19$ |
| GJ clockwise, $T = 0\ kN$ (kNm$^2$) | $14.5 - 56$ | $44.7$ | $44.3$ | $45.4$ |
| Coupling clockwise − torsion/tension (rad/m) | | $182$ | $188$ | $180$ |
| GJ anticlockwise, $T = 0\ kN$ kN (kNm$^2$) | $15.9 - 17.2$ | $19.1$ | $19.5$ | $18.7$ |
| Coupling anticlockwise \| torsion/tension, (rad=m) | | $-406$ | $-330$ | $-343$ |

## 4.2 Loxodromic assumption in bending response

DNV GL along with Ultra Deep launched a Joint Industry Project (JIP) to validate the loxodromic assumption, which is used in local analysis stress calculations of umbilicals and flexible pipes. The validation was done by comparing calculations with high quality bending test measurements. Validation against high/low tension bending tests is considered to cover umbilicals installed at normal to deep water depths. Details of the validation methodology and sample results are presented in /5/, /6/ and /7/.

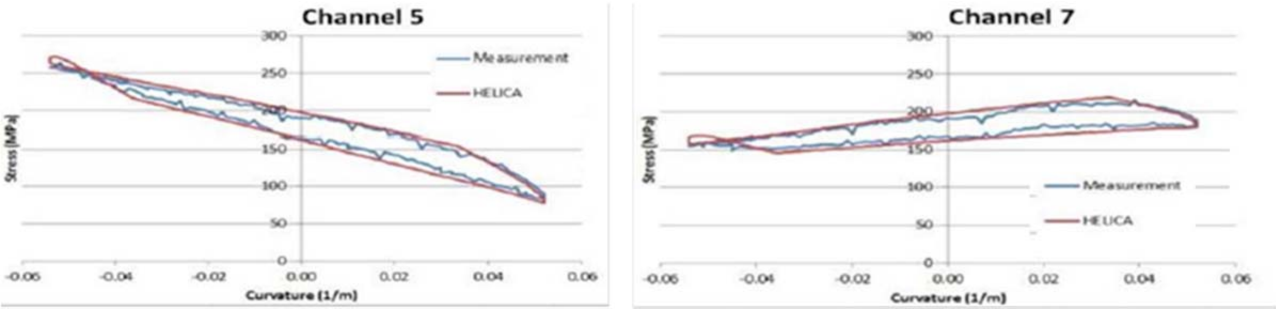
The Helica results compare remarkeably well with test stress measures. The test set-up and outline are depicted at the top figure in Figure 4-1.

**Figure 4-1 Upper: High tension test – test set-up, cross-section and sensor locations.**



Example of strain gauge positions

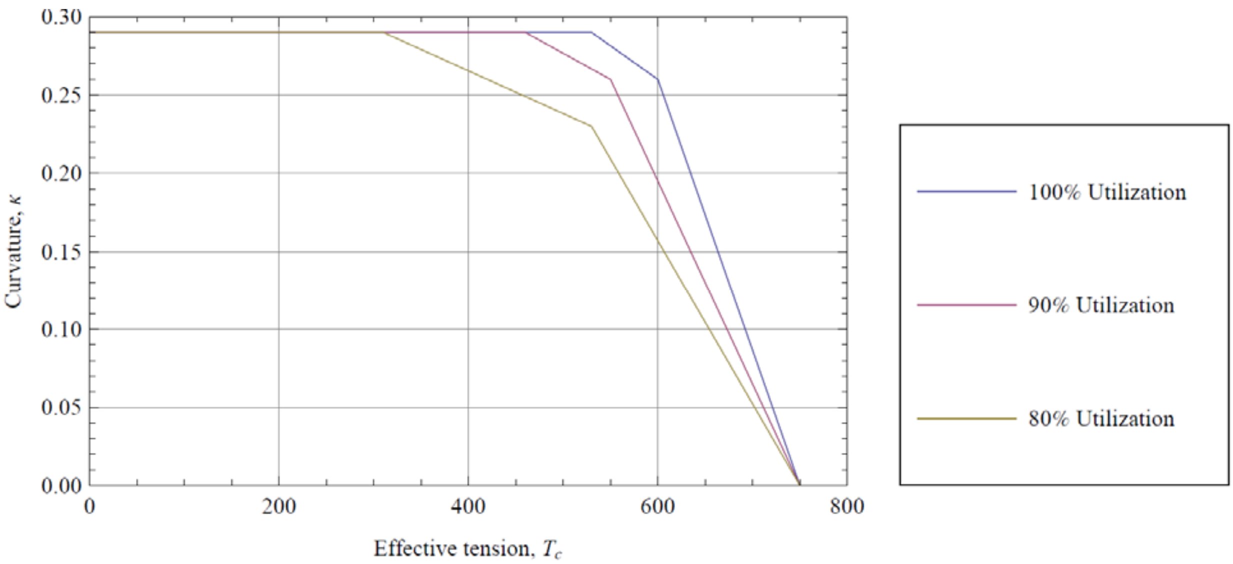
**Figure 4-2 Helica versus measurements - small tubes.**



# 5 CAPACITY CURVES

The extreme stress capacity is most conveniently determined in terms of a cross-sectional capacity curve. ISO 13628-5 Subsea umbilicals  describes allowable combinations of curvature and effective tension that can be applied to the cross-sectionwithout compromising the structural integrity of the interior strength and functional elements. Examples of umbilical capacity curves are shown in Figure 5-1 for different utilization levels reflecting different modes of operation, for example, installation and in-place operation. The utilization level is defined according to allowable stress levels, $\sigma_a$, related to the yield stress, $\sigma_a = k_u \cdot \sigma_y$, where $\sigma_y$ denotes the yield stress, and $k_u$ is a utilization factor. Similar considerations also hold for strains that are typically used for plastic sheaths. The methodology as outlined in the previous section is applied to determine stresses in all interior elements for combined tension and curvature loading. The utilization in each component is evaluated against acceptance criteria given in relevant design codes. The capacity curve is finally established as the allowable effective tension and curvature combinations that ensure that the stresses in all interior elements fulfill the defined acceptance criteria. A recursive calculation scheme is applied for consistent calculation of capacity curves of cross-sections with higherorder composite helix elements, for example, cables applied in helix geometry in the crosssection.

**Figure 5-1 Example of umbilical capacity curves.**



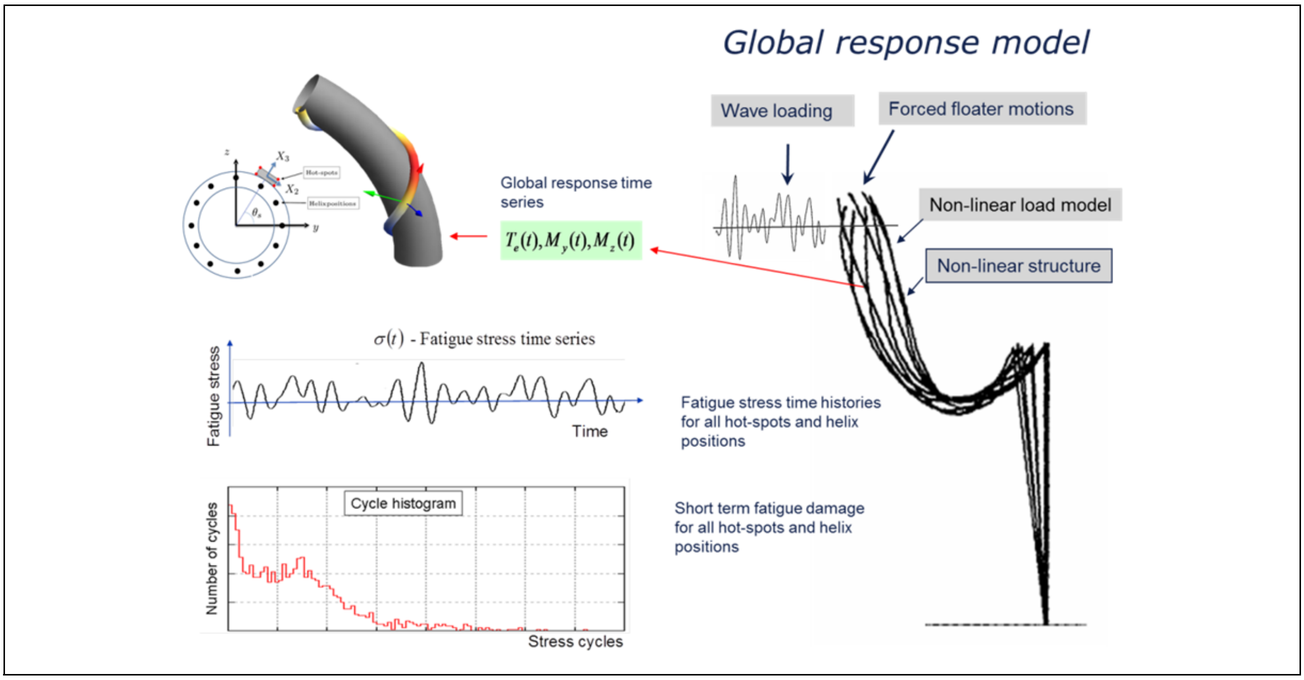
# 6 SHORT-TERM FATIGUE ANALYSIS

The purpose of short-term fatigue analysis is to assess the fatigue damage in a stationary short-term environmental condition considering fatigue loading in terms of time-series of simultaneous bi-axial curvature and effective tension produced by global dynamic response analysis. The required input to this type of analysis is:

- Fatigue stress analysis of helix elements considering stick-slip behaviour in bending
- Highly efficient and robust calculation scheme
- Calculation of consistent fatigue stresses by direct application of global response time series as external loading
- Fatigue stress cycles are established by Rain Flow Counting (RFC) at all hotspots/locations considered in the analyses. This allows for consistent fatigue damage assessment for regular as well as irregular fatigue analyses.

A key feature is that the fatigue analysis is carried out for the helix elements one by one. Analysis of several helix elements within the same cross section will require one full fatigue analysis per element. This enables a highly efficient calculation scheme allowing for a fully consistent link between global analyses and the local fatigue damage calculation scheme in Helica. As shown in time series of bi-axial cross-sectional curvature and effective tension time series are applied directly as loading in the local fatigue stress analysis. This means a full cross sectional analysis is carried out per time step of the loading processes produced by the global response analysis ensuring full consistency.

**Figure 6-1 Link between global and local response models in fatigue analyses.**




The output from the analysis is short-term fatigue damage and stress cycle distributions to be applied in subsequent long-term fatigue analysis.

# 7 REFERENCES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/3/ Skeie, G. Helica — Theory manual, DNV, 2010, DNV Report 2010-0195

/4/ Sødahl, N; Steinkjer, O.; Bahiense, R; Helica — User Manual, DNV, 2009.

/5/ ISOPE 2016-TPC-1060 'Validation of Umbilical Fatigue Analysis by Full-Scale Testing' Mayuresh M Dhaigude, Knut I. Ekeberg and Nils Sødahl

/6/ ISOPE 2016-TPC-1294 ' Validation of the Loxodromic Bending Assumption Using High-quality Stress Measurements', Knut I. Ekeberg

/7/ ISOPE 2016-TPC-1307 'Validation of the Loxodromic Bending Assumption Using High-quality Stress Measurements – High Tension Case' Mayuresh M. Dhaigude and Knut I. Ekeberg

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