ULTRA DEEP, LLC

TxIS TEXAS INSTITUTE OF SCIENCE

# Problem Statement re. FE-based Calculation of BS Performance

## 00000-INT-TN-KIE-20151109-1 Rev. 1

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**Nov. 17, 2015**

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# 1 INTRODUCTION

Bend stiffeners are widely used in the Oil & Gas industry when floating production is concerned. Umbilicals are the “lifeline” between the control room and the subsea well; power cables may provide power to subsea pumps; and various forms of risers are used to pump water into the reservoir and, last but not least, used to transport the produced oil or gas up to the platform.

One thing that all these cables and risers have in common, is that they must be protected from overbending and fatigue at the riser/vessel interface. A bend stiffener is a device that provides a gradual stiffness distribution from the riser’s own stiffness to the vessel’s near “infinite” stiffness, and, if designed properly, it will be able to provide the riser with the necessary protection over its entire design life.

The picture below shows a bend stiffener that is connected to the vessel in air, although the more common approach is to connect it under water at or near the bottom of the floating production unit.

**Figure 1. Bend stiffener (yellow) and riser (black) hung off in air (Trelleborg brochure).**

 

Sometimes it is necessary to be able to calculate the bend stiffener’s performance under laboratory conditions, where the bend stiffener may not be installed vertically as indicated in Figure 1, but horizontally, as indicated in the figure below.

**Figure 2. Bend stiffener and umbilical under full-scale testing conditions.**

Under laboratory conditions, the bend stiffener’s mass distribution may therefore affect the performance.

The most common material to produce bend stiffeners from is steel (interfacing flange) and polyurethane (PU). One challenging aspect of this is that PU is a very non-linear material and that its stiffness is very temperature sensitive as exemplified in the following graph.

 

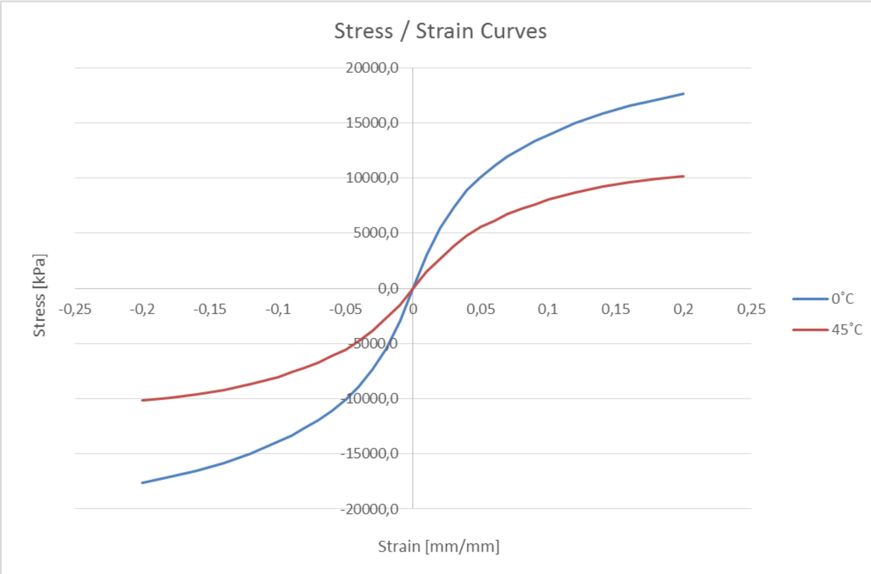


**Figure 3. Examples of PU stress-strain curves at 0 and 45 deg. C.**

Although the bend stiffener under in-service conditions has a constant temperature, cyclical effects must be accounted for (summer vs. winter). In addition to that, certain risers may have a higher temperature than its surroundings (e.g. power cables and risers with high-temperature content) thereby affecting the bend stiffener's stiffness.

Ideally, a bend stiffener design tool should be able to account for these mentioned effects.

# 2 ABBREVIATIONS AND DEFINITIONS

| | | | | | |
|---|---|---|---|---|---|
| BM | - | Bending Moment | PU | - | Polyurethane |
| BS | - | Bend Stiffener | QA | - | Quality Assurance |
| FE | - | Finite Element | TN | - | Tension |
| ID | - | Inner Diameter | V | - | Shear force |
| OD | - | Outer Diameter | | | |

 

# 3 EXAMPLE

The best way to illustrate what the calculation engine we are after is doing, is maybe to show an example with our existing tool that uses a shooting method.

The figure below shows all the input information necessary to perform a calculation using linear material properties. The input covers the geometric information about a given bend stiffener, riser outer diameter and bending stiffness, and the linear elastic modulus of the PU material.

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**INPUT BS GEOMETRY:**

| | | | |
|---|---|---|---|
| **Geometrical Properties:** | | | |
| - Stiff straight section length | 647.3 | mm | |
| - Conical Length | 6000 | mm | |
| - Tip straight section length | 200 | mm | |
| - Root OD | 1000 | mm | |
| - Tip OD | 325 | mm | |
| - ID | 285 | mm | |
| **Material Data (for linear calculations only):** | | | |
| - E-modulus | 195.000 | MPa | |
| - Limiting strain | 10% | | |
| **Umbilical Data:** | | | |
| - Umbilical OD | 270 | mm | |
| - Umbilical EI | 102.6 | kNm$^2$ | |
| - MBR | 9 | m | |
| (curvature) | 0.11111111 | | |
| - Riser length (in model) | 3.00 | m | SUCCESS |
| **BS Volume** | | | |
| - Straight section | 467.1 | liter | |
| - Conical section | 1864.5 | liter | |
| - Tip section | 3.8 | liter | |
| | 2335.4 | liter | |
| **PU mass:** | | | |
| - PU density | 1130 | kg/m3 | |
| - Mass | 2639.0 | kg | re = 285 mm |
| | | | Tip OD = 325 mm |

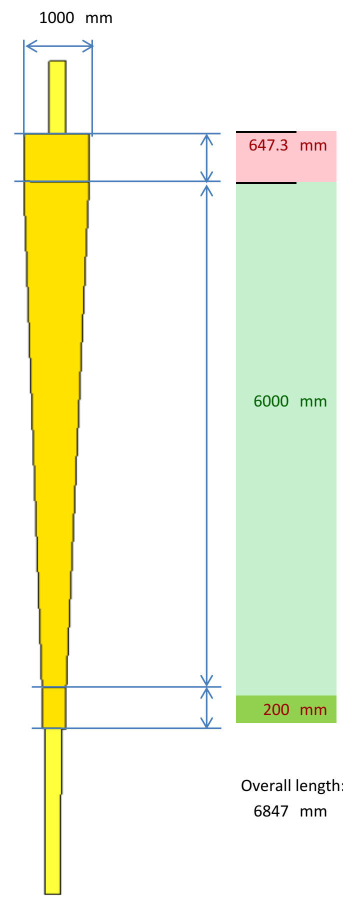





**Figure 4. Input information.**

The stress-strain relationship for PU under a given temperature is necessary to be able to perform bending performance under non-linear conditions.

**INPUT PU STRESS-STRAIN CURVE (no limit re. no. of points):**

| STRAIN | STRESS | |
|---|---|---|
| [-] | [MPa] | [Pa] |
| 0 | 0 | 0 |
| 0.005 | 1.35233008 | 1,352,330 |
| 0.01 | 2.5625939 | 2,562,594 |
| 0.015 | 3.59709335 | 3,597,093 |
| 0.02 | 4.47697085 | 4,476,971 |
| 0.025 | 5.22167412 | 5,221,674 |
| 0.03 | 5.84902102 | 5,849,021 |
| 0.035 | 6.37526429 | 6,375,264 |
| 0.04 | 6.81515642 | 6,815,156 |
| 0.045 | 7.18201435 | 7,182,014 |
| 0.05 | 7.48778438 | 7,487,784 |
| 0.055 | 7.74310685 | 7,743,107 |
| 0.06 | 7.95738102 | 7,957,381 |
| 0.065 | 8.13882986 | 8,138,830 |
| 0.07 | 8.29456477 | 8,294,565 |
| 0.075 | 8.43065049 | 8,430,650 |
| 0.08 | 8.55216979 | 8,552,170 |
| 0.085 | 8.66328835 | 8,663,288 |
| 0.09 | 8.76731949 | 8,767,319 |
| 0.095 | 8.86678902 | 8,866,789 |
| 0.1 | 8.9635 | 8,963,500 |
| 0.105 | 9.05859755 | 9,058,598 |
| 0.11 | 9.15263365 | 9,152,634 |
| 0.115 | 9.24563192 | 9,245,632 |
| 0.12 | 9.33715245 | 9,337,152 |
| 0.125 | 9.42635654 | 9,426,357 |
| 0.13 | 9.51207157 | 9,512,072 |
| 0.135 | 9.59285572 | 9,592,856 |
| 0.14 | 9.66706282 | 9,667,063 |
| 0.145 | 9.73290713 | 9,732,907 |
| 0.15 | 9.78852813 | 9,788,528 |

**No. of data points:** 31

**Regression coefficients:**

| C6 | C5 | C4 | C3 | C2 | C1 |
|---|---|---|---|---|---|
| 8.38562E+11 | -2.40363E+11 | -47089027688 | 26896012192 | -4128100628 | 296334572.8 |

**Check:**

| | | |
|---|---|---|
| Input Strain: | 0.05 | |
| Output Stress: | 7,502,161 | Pa |
| | 7.50 | MPa |

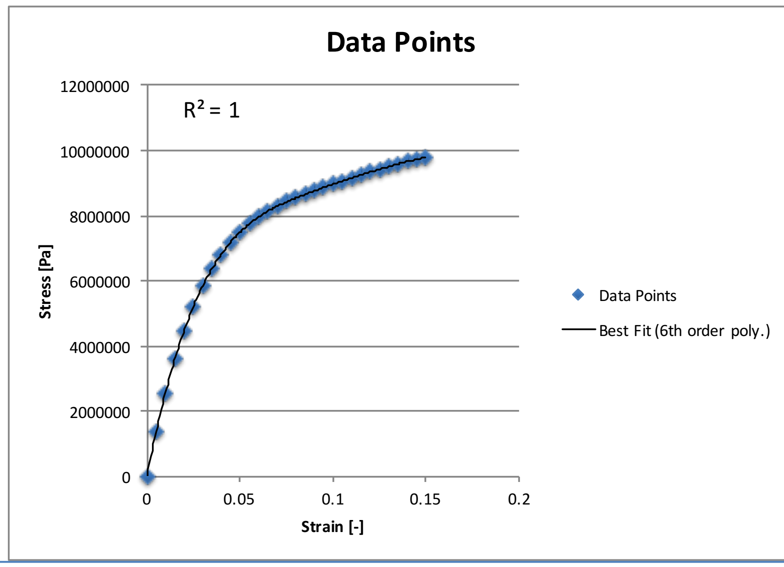
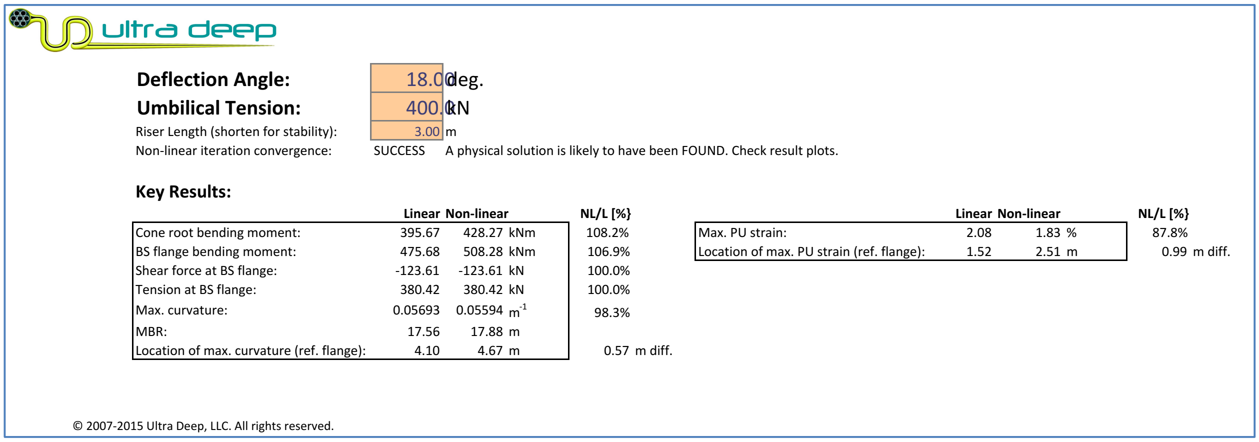



**Figure 5. Non-linear stress-strain relationship of the given PU material.**

The next input is the load case information; the riser tension and the applied deflection angle. The calculation is more or less instantaneous, and the key parameters for both the linear and non-linear calculation are compared.



**Deflection Angle:** 18.00 deg.

**Umbilical Tension:** 400.0 kN

Riser Length (shorten for stability): 3.00 m

Non-linear iteration convergence: SUCCESS A physical solution is likely to have been FOUND. Check result plots.

**Key Results:**

| | Linear | Non-linear | | NL/L [%] |
|---|---|---|---|---|
| Cone root bending moment: | 395.67 | 428.27 | kNm | 108.2% |
| BS flange bending moment: | 475.68 | 508.28 | kNm | 106.9% |
| Shear force at BS flange: | -123.61 | -123.61 | kN | 100.0% |
| Tension at BS flange: | 380.42 | 380.42 | kN | 100.0% |
| Max. curvature: | 0.05693 | 0.05594 | $m^{-1}$ | 98.3% |
| MBR: | 17.56 | 17.88 | m | |
| Location of max. curvature (ref. flange): | 4.10 | 4.67 | m | 0.57 m diff. |

| | Linear | Non-linear | | NL/L [%] |
|---|---|---|---|---|
| Max. PU strain: | 2.08 | 1.83 | % | 87.8% |
| Location of max. PU strain (ref. flange): | 1.52 | 2.51 | m | 0.99 m diff. |



**Figure 6. Load case input (tension and deflection angle) and key results.**

Then finally different kinds of result plots are presented:

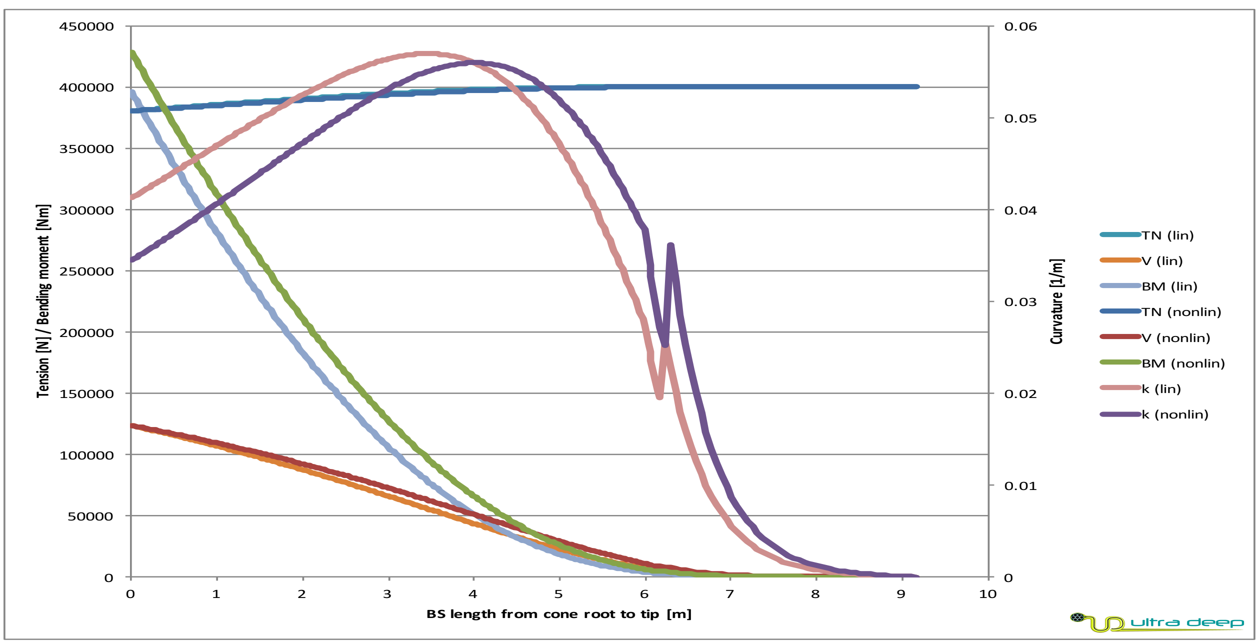



**Figure 7. Curvature-, moment-, shear force- and tension distribution through the bend stiffener (linear and non-linear).**

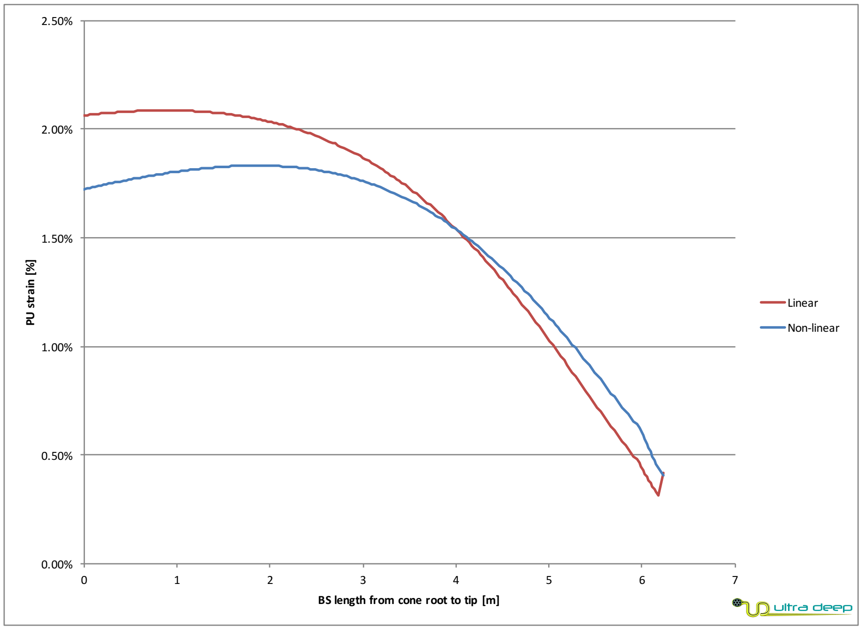



**Figure 8. PU strain distribution (linear and non-linear).**

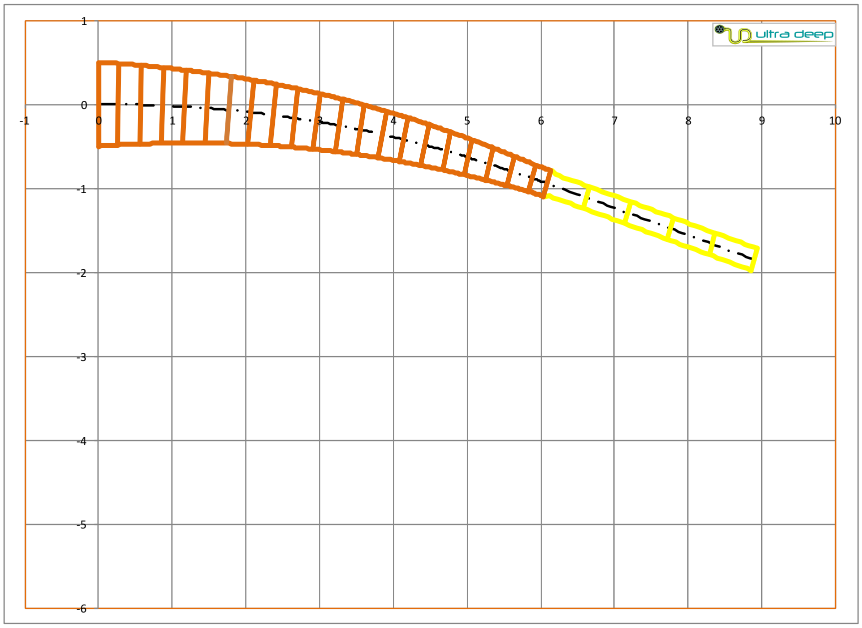



**Figure 9. Bend stiffener/riser bent geometry.**

# 4 PROBLEM STATEMENT

Ultra Deep is looking for a stable and robust numerical solver based on the Finite Element Method that can calculate the “bending of a cantilever beam” problem as it relates to the riser/bend stiffener situation as described earlier in this document.

The applications using the numerical engine will be programmed by Ultra Deep engineers.

DLL API

## 4.1 Introduction

### 4.1.1 Purpose

The purpose of this chapter of the Problem Statement Document is to specify in more detail the requirements for a Finite Element-based software that will be part of several applications that Ultra Deep has planned that is concerned with the design and analysis of riser/bend stiffener performance under tension and deflection.

### 4.1.2 Scope

The name of the software shall be “BS-engine”.

The software shall be suitable for being used by user applications programmed by Ultra Deep engineers at a later stage, via an API, as a DLL or as an EXE file.

The software shall use the Finite Element Method to solve the “bending of a cantilever beam” as it relates to the riser/bend stiffener situation, and, as a function of the input parameters (described later) calculate and output the bent geometry, as well as the tension-, shear force-, moment-, and curvature distribution as a function of the FE-model length. The program shall be able to use both linear and non-linear material properties, it shall be able to account for a radial temperature gradient through the stiffener material, and it shall be able to account for the mass distribution of the stiffener and user specified nodal forces.

Although Ultra Deep’s main goal with the software is to use it internally, it is also Ultra Deep’s intention to create user applications that will be offered to the market. With this in mind, it is important that the software includes features that enhances the numerical stability without user interference.

## 4.2 Overall Description

### 4.2.1 Product Perspective

The "BS-engine" software shall be part of a dynamic riser analysis suite of softwares that includes:

- UmbiliCAD®
- OrcaFlex/RIFLEX

UmbiliCAD® is a tool used to design/draw umbilical and cable cross-sections and to calculate their associated mechanical properties and capacities, for subsequent input to the riser analysis program.

OrcaFlex and RIFLEX are two different riser analysis programs, of which Ultra Deep is a user of both. A riser analysis program uses the full global system description, including water depth, vessel and vessel motions, environment (waves and current) and risers (with associated mechanical properties), to calculate the mechanical response in the riser under different conditions, by simulations in the time domain.

When a dynamic riser system is designed, hundreds or thousands of simulations are performed under environmental conditions ranging from the statistical "day-to-day" conditions to the most severe 100-year hurricane conditions. The most severe of these conditions are initially simulated with the riser hinged to the vessel interface. The tension vs. deflection angle at this interface is recorded and a "bend stiffener design contour" is created by identifying the most extreme acting deflection angle under different acting tensions.

The design contour is transformed to a number of tension vs. deflection angle load cases that can be analyzed by "BS-engine" after the design engineer has come up with an initial bend stiffener design geometry. Each curvature distribution output from "BS-engine" is compared to the allowable curvature at each load case's tension. If the curvature calculated by "BS-engine" is larger than the allowable, the design engineer must manipulate the bend stiffener geometry and re-run the load cases of the "load contour". This process is repeated until every max. curvature calculated by "BS-engine" is smaller than or equal to the max. allowable.

When a working bend stiffener design is achieved, the design is implemented into the FE-model of the riser analysis program, and every load case is re-run to confirm that the BS design is working.

Ultra Deep will develop applications where "BS-engine" will be used. These applications will need to run several instances of "BS-engine" simultaneously, and will need to use results from all these instances to manipulate the input (BS geometry and/or material properties) and re-run "BS-engine" in several instances simultaneously, until certain predetermined conditions are fulfilled.

#### *4.2.1.1 System Interfaces*

Inputs:

In the short term “BS-engine” will have a user generated text-file based input file read from the hard-disk. An API shall be developed for data exchange with other applications.

Outputs:

In the short term “BS-engine” will have a text-file based output file written to the hard-disk. An API shall be developed for data exchange with other applications.

#### *4.2.1.2 User Interfaces*

It should be possible to run “BS-engine” as a command-line executable EXE file where “BS-engine” reads a text-based input-file (e.g. “C:\BS-engine.exe input.inp”) and generates a text based output-file (e.g. output.res”). This is useful in the short term for QA and testing purposes.

When “BS-engine” is run via another application, there should be no direct user interference.

#### *4.2.1.3 Hardware Interfaces*

“BS-engine” shall have the capability to write text-based result file(s) to the hard-disk.

#### *4.2.1.4 Software Interfaces*

All input and output to “BS-engine” shall be defined in an API.

### 4.2.2 Product Functions

1. The “BS-engine” shall be able to read the user-defined input file. This input file shall contain information regarding the type of analysis to run; FE-discretization; BS geometry and material information; riser mechanical properties; relevant environmental data; and the load case to analyze.
2. If indicated in the input file, the first step for “BS-engine” to do is to calculate the radial temperature distribution in the BS based on the surface temperature of the riser, each involved material’s thermal conductivity, and the ambient temperature. Based on the achieved result, “BS-engine” will select the appropriate elastic modulus or stress-strain curve for the elements in the FE-model.
3. The major part of the “BS-engine” application with respect to processing will be the finite element (FE) engine. The FE engine shall use the user defined BS geometry and the applicable elastic-modulus and/or stress-strain curves, along with the load case (tension and deflection angle) to calculate the BS/riser bending performance.

4. “BS-engine” shall write a results file that shall contain a summary of the input used; a key result summary; and detailed nodal results.

### 4.2.3 User Characteristics

The users of “BS-engine” and associated applications will typically be riser analysis engineers at B.Sc. and M.Sc. level.

### 4.2.4 Constraints

Parallel operation

The application itself does not need to be possible to utilize parallel functionality, but it must be possible to run several instances of the application by a multi-thread processor simultaneously without problems.

Control functions

The “BS-engine” application needs to have control functions to the level that it will be considered as being “user friendly”. By that is meant that if a user attempts to run the program e.g. without having defined all necessary inputs, the program must provide a meaningful error message.

Reliability requirements

Since it is Ultra Deep’s intention to use “BS-engine” as part of applications that will be made available to the market, emphasis must be placed on reliability in terms of numerical stability. “BS-engine” must be able to find the solution without user interference and/or the necessity for the user to adjust parameters associated with the numerical method applied.

## 4.3 Specific Requirements

1. The "BS-engine" shall be able to read the user-defined input file. This input file shall contain the following information:
   - Identification of type of analysis to run:
     - Linear
     - Non-linear
     - Linear and non-linear
     - Constant temperature
     - Temperature gradient
     - No mass influence
     - Mass influence (equivalent to horizontal set-up with bending in the vertical plane)
     - No user-defined nodal forces present
     - User-defined nodal forces present
     - Bending performance in air (relevant for heat transfer calculations)
     - Bending performance under water (relevant for heat transfer calculations)

   - FE-discretization (unless it is possible to use a default and have adaptations during the analysis to achieve stabililty)
     - Longitudinal
     - Radial
     - The FE-discretization needs to be general enough to accommodate Ultra Deep's modular bend stiffener concept. In the modular bend stiffener concept, the bend stiffener is split in three segments radially and in two or more longitudinally. The radial split will not need to be accommodated by "BS-engine", but the longitudinal split(s) will have metallic connecting flanges, which will represent short segments of increased bending stiffness. This will need to be accommodated be "BS-engine".

   - Riser data:
     - OD
     - Axial stiffness
     - Bending stiffness
     - Mass per meter
     - Surface temperature (if applicable)

- Bend stiffener geometry (should be able to define as generally as possible, but typically includes):
    - Root OD
    - Length of “stiff straight root section” (if applicable)
    - Length of conical section
    - Length of “straight tip section”
    - Internal bore

- Material data (stiffener material, typically PU):
    - Elastic modulus (for linear calculations)
        - For different temperatures (if applicable)
    - Stress-strain tables (for non-linear calculations)
        - For different temperatures (if applicable)
    - Density (if applicable)
    - Thermal conductivity (if applicable)

- Environmental data
    - Ambient temperature (if applicable)
    - Seawater density (if applicable)
    - Seawater thermal conductivity (if applicable)
    - Air thermal conductivity (if applicable)

- Load case
    - Riser tension (force to be applied at the end of the riser coming out of the BS)
    - Deflection angle (force angle)

2. If indicated in the input file, the first step for “BS-engine” to do is to calculate the radial temperature distribution in the BS based on the surface temperature of the riser, each involved material’s thermal conductivity, and the ambient temperature. Based on the achieved result, “BS-engine” will select the appropriate elastic modulus or stress-strain curve for the elements in the FE-model.

3. The major part of the “BS-engine” application with respect to processing will be the finite element (FE) engine. The FE engine shall use the user defined BS geometry and the applicable elastic-modulus and/or stress-strain curves, along with the load case (tension and deflection angle) to calculate the following:
   - Deflected geometry
   - Riser tension distribution
   - Riser shear force distribution
   - Riser bending moment distribution
   - Riser curvature distribution
   - Bend stiffener max strain distribution (surface)

4. The following information shall be written to “BS-engine’s” output file:
   - A summary of all inputs used
   - A key result summary:
     - BS root bending moment
     - BS root shear force
     - Max curvature
     - Location of max curvature (distance from BS interface flange)
     - Max stiffener strain
     - Location of max stiffener strain (distance from BS interface flange)
   - All FE-model nodal results (for the riser center line)
     - Tension
     - Bending moment
     - Shear force
     - Curvature
     - Stiffener surface strain

# 5 REQUEST FOR QUOTATION

## 5.1 Objectives

Develop "BS-engine" with the following functionality:

- Calculation of bending performance of bend stiffener and riser ("cantilever beam") when the riser is subjected to a tension at a deflection angle using the finite element method.
- Temperature module (OPTIONAL, please indicate project cost with and without this functionality).
- Linear and non-linear material properties.
- Horizontal set-up with and without mass influence, including the ability for user-defined nodal forces.

## 5.2 Deliverables

Source code and executable "BS-engine", including all IP-rights and the ability to sell UD-developed software bundled with "BS-engine" royalty free.

## 5.3 Schedule and Cost

Please provide UD with your best price and schedule.