ULTRA DEEP, LLC

Development of Application “UltraBend™” for Bend Stiffener Design

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1 INTRODUCTION

Bend stiffeners are widely used in the Oil & Gas industry when floating production is concerned. Their task is to protect risers (umbilicals and flowlines) from excessive bending. Umbilicals are a type of cable. It constitutes the “lifeline” between the control room of the floating production unit (platform) and the subsea oil/gas well by providing any combination of different kinds of functions such as electric power; hydraulic power; chemical injection capabilities; electrical communication and fiber optic communication. Various forms of flowlines are used to pump water into the reservoir and to transport the produced oil and/or gas from the reservoir back 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. A BS in service will always be installed in a near-vertical orientation.

Figure 1. Bend stiffener (yellow) and riser (black) hung off in air on a floating oil production facility (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.

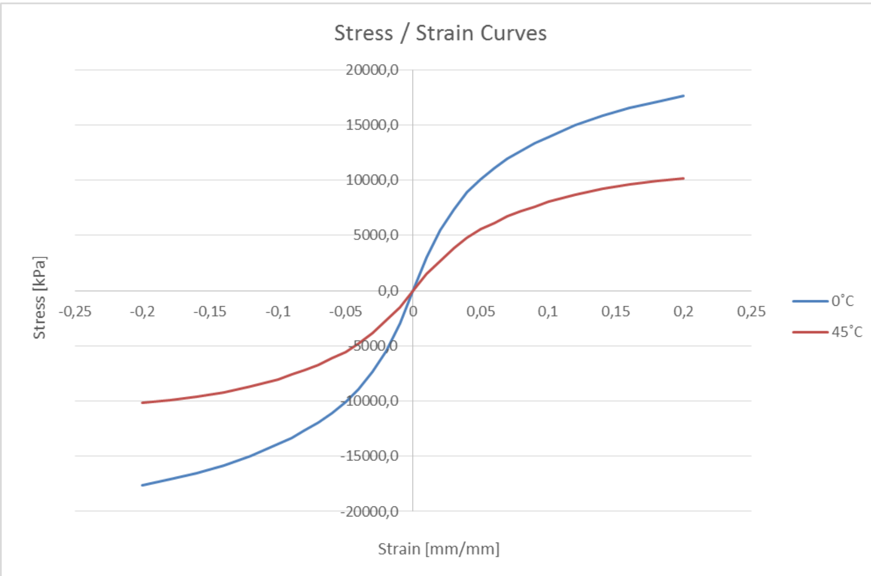

Figure 3. Examples of PU stress-strain curves at 0 and 45 deg. C.

Although the bend stiffener under in-service conditions has a relatively 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 calculation tool should be able to account for these mentioned effects.

2 REFERENCES

[1] DNV GL document (unnumbered) “BS-engine USer Manual” dated 06-04-2016.

[2] UD Doc. “UltraBend DETAILED DESCRIPTION.mmap” (MindManager file)

3 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			

4 EXAMPLE

The best way to illustrate what information is necessary to calculate a BS’ performance, and the resulting information, is to show an example.

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.

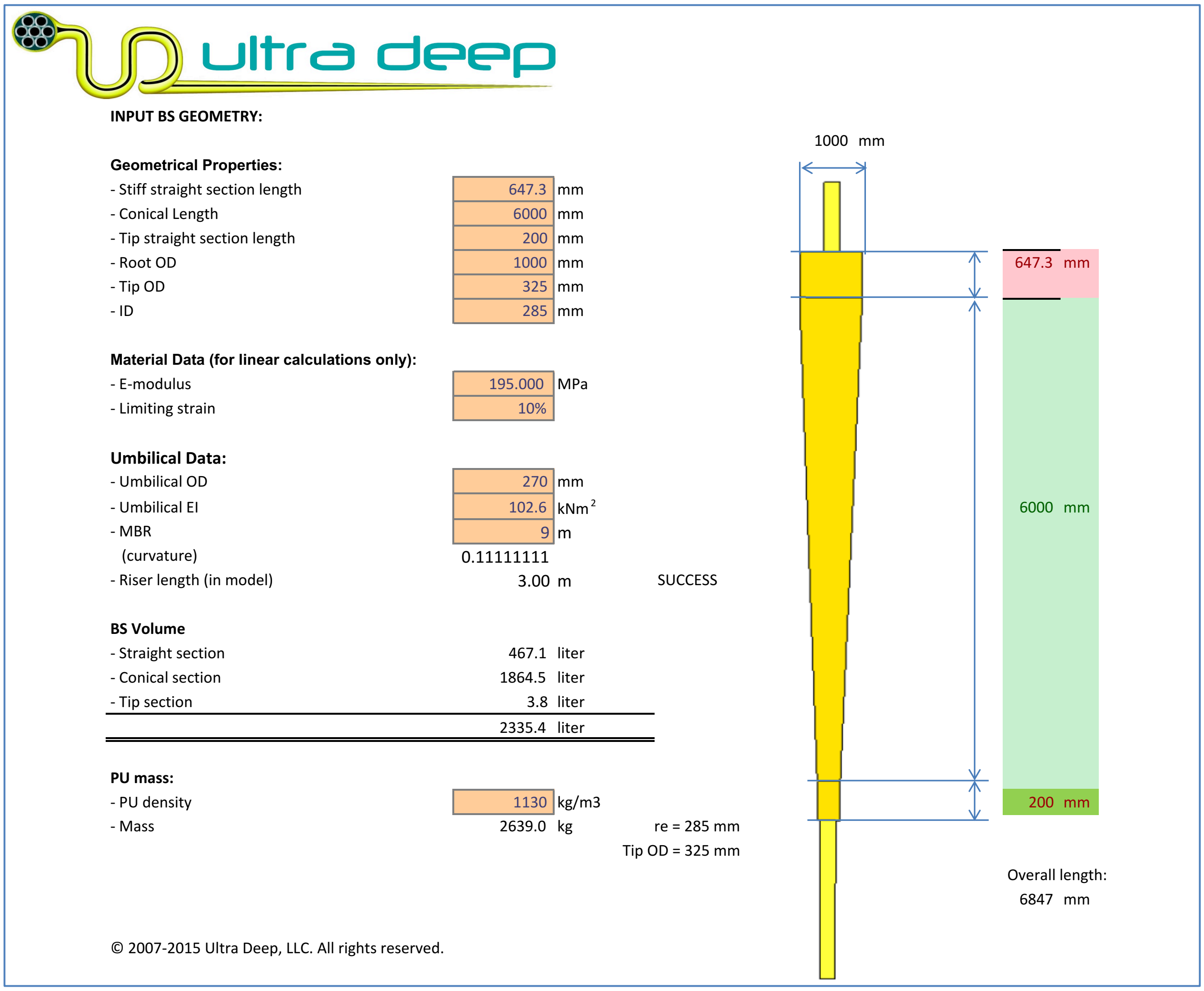

Figure 4. Input information.

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

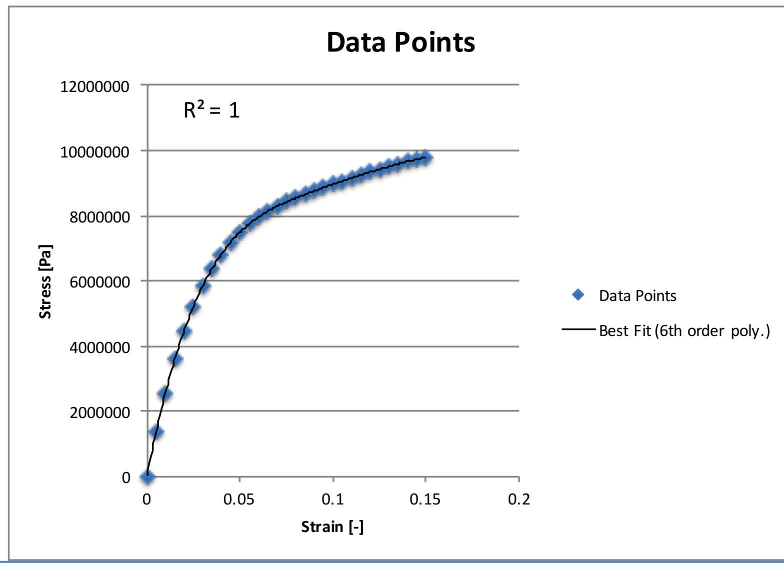

Figure 5. Non-linear stress-strain relationship of the given PU material.

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.

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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.

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

Then finally different kinds of result plots are presented:

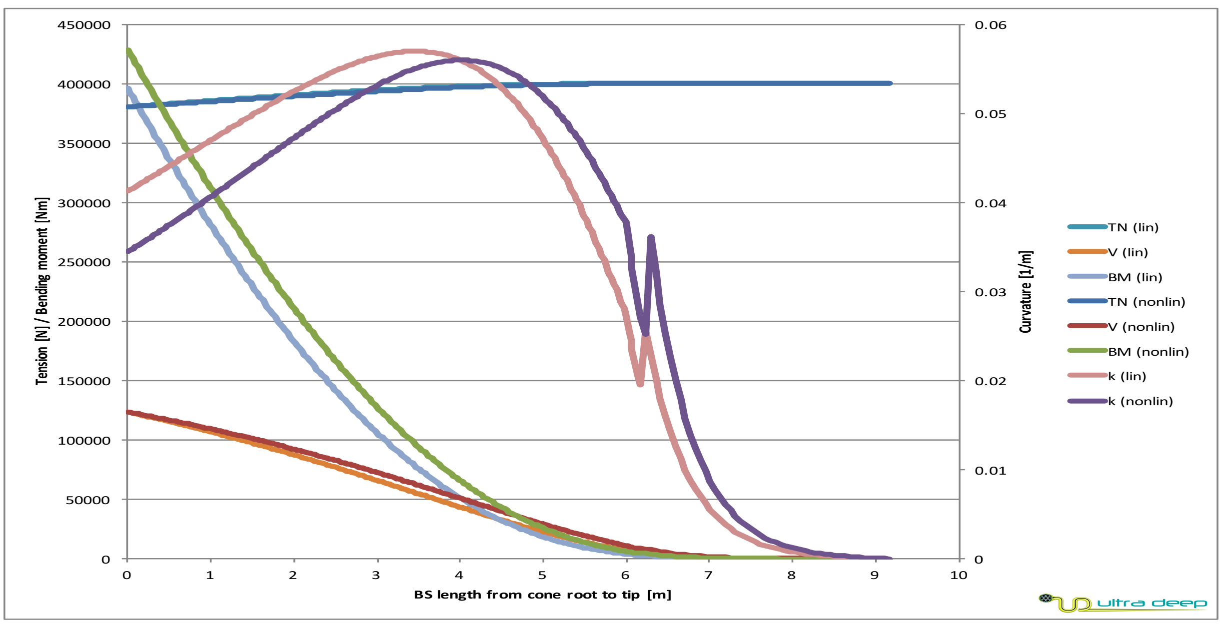


Figure 7. Curvature-, moment-, shear force- and tension distribution through the bend stiffener (linear and non-linear).

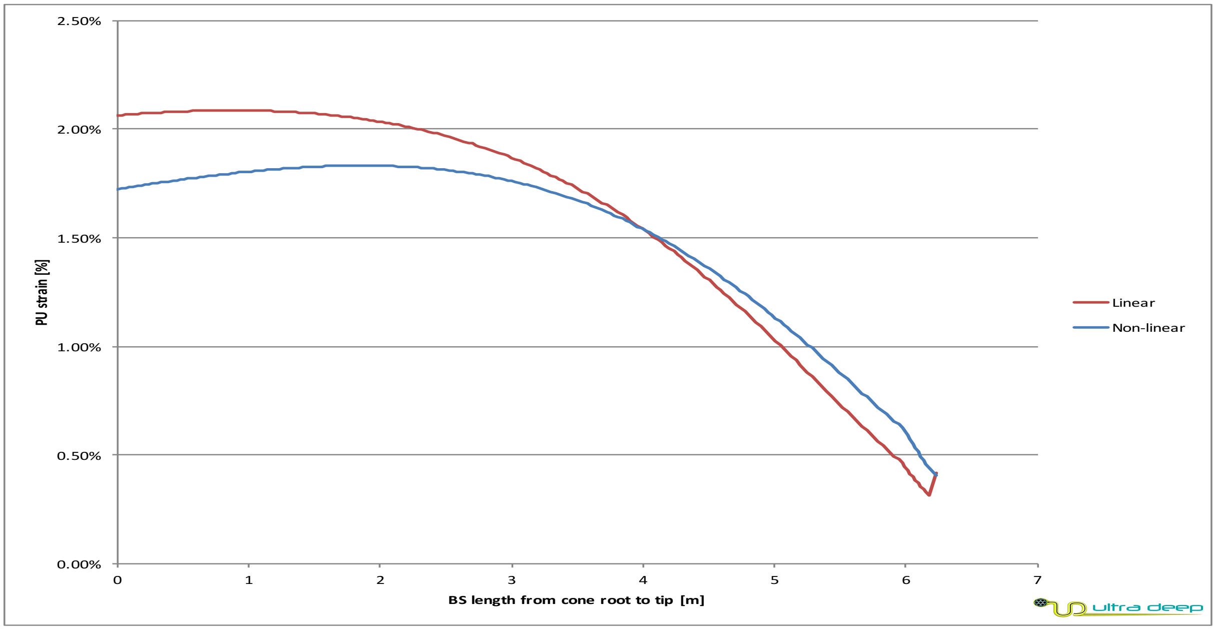


Figure 8. PU surface strain distribution (linear and non-linear).

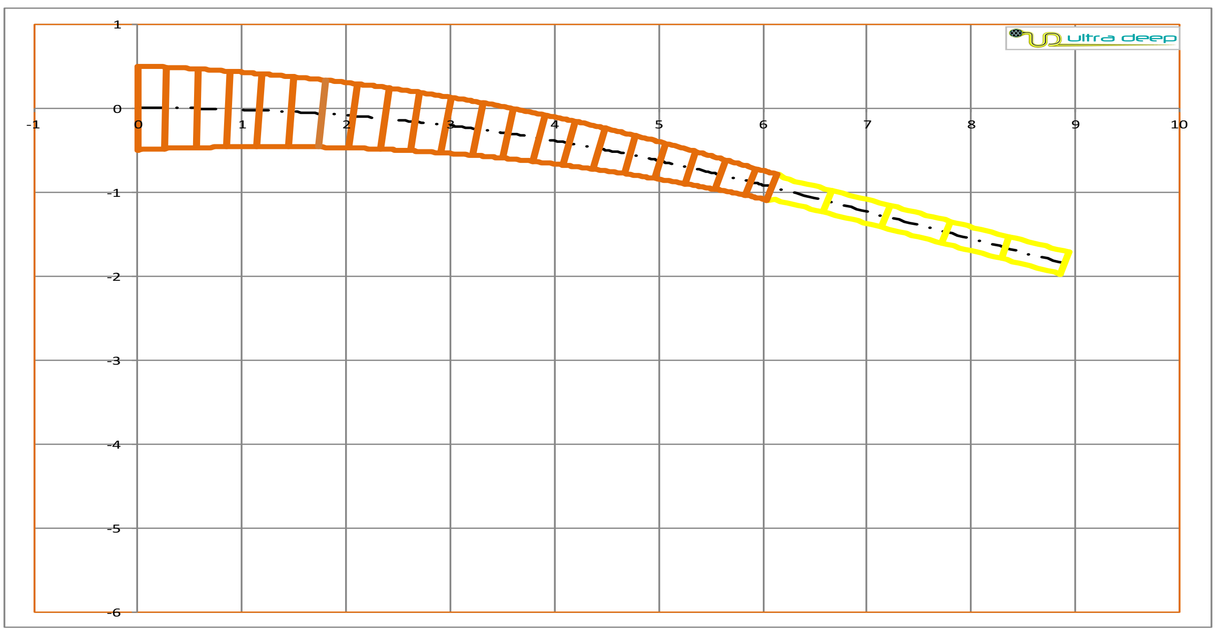


Figure 9. Bend stiffener/riser bent geometry.

5 ULTRABEND BS DESIGN SOFTWARE

5.1 Introduction

UD has already developed an FE-based program that calculates the bending performance of a given riser with known mechanical properties, acting together with a known BS geometry with given material properties, under a given load case. This software is called BS-engine and will be described in further details shortly.

The goal, however, is to develop a BS design software. The difference between a BS performance software and a BS design software is philosophic in nature. With a performance software, the riser and BS are known, the load case they are subjected to is known, and the curvature distribution and interface loads are calculated. With a design software, the riser is known, the riser's load capacity is known, the acting load cases are known, and the size of the necessary BS is calculated.

This design application is called UltraBend™ and it will use the already developed BS-engine to arrive at the optimized bend stiffener for each specific case.

5.2 UltraBend Design Context

The UltraBend application with BS-engine shall be part of a dynamic riser analysis suite of softwares that includes:

- UmbiliCAD®
- OrcaFlex

UmbiliCAD® (owned and patented by UD) 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 (owned by Orcina, UK) is a riser analysis program. 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 environmental conditions, by simulations in the time domain.

Here is a brief description of the design process using BS-engine, but before the existence of UltraBend. When a dynamic riser system is designed, hundreds or sometimes even 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.

The problem with this approach is that even though the design engineer has arrived at a BS design that works, he has no way of knowing if the achieved design is size-optimum. Or, formulated as a question, is it possible to find a smaller bend stiffener that still fulfills the performance requirements? Since even an optimized BS may be 8 m long, have a 1-m root diameter or more, and weight several tons, it is extremely important to be able to perform a design optimization based on the BS geometry.

UltraBend shall therefore be an application that uses BS-engine to perform design optimization calculations. UltraBend must be capable of running several instances of "BS-engine" simultaneously, and it will need to use results from all these instances to manipulate BS-engine's input (BS geometry and/or material properties) and re-run "BS-engine" in several instances simultaneously, until the predetermined conditions are fulfilled.

5.3 FE-based FORTRAN-program "BS-engine"

5.3.1 General Description

DNV GL in Norway has programmed "BS-engine" for UD. The following general description of BS-engine is taken from the documentation DNV GL provided to UD along with the application.

BS-engine is a tailor-made software for static analysis of bend stiffeners using the finite element method. The FE-solver is a self-contained subroutine package with a well-defined data structure interface to the driver program (i.e. main program, in this context the BS-engine). The driver program is typically tailor-made for each application to facilitate easy user interface and analysis set-up requirements (e.g. structural modeling and meshing, set-up of data structure for FE-solver, load application sequence etc). The following functionality of the FE-solver is of relevance for BS modeling/analysis:

- 3D non-linear static solver with an iterative load incrementation solution scheme
- A co-rotational formulation is applied allowing “unlimited” displacements and rotations in 3D space
- 3D beam elements with linear material modeling and geometric stiffness
- 3D beam elements with non-linear elastic material modeling in bending (moments vs. curvature) and geometric stiffness
- Boundary conditions (foxed/free) at any node in the FE-model
- Application of point loads at any node in the FE-model
- Loading due to volume forces (weight and buoyancy)

5.3.2 Inputs and Outputs

How to use BS-engine is described in [1]. BS-engine can be used as a stand-alone application, in which case the user will edit an ASCII input file that contains the following information:

- A bend stiffener specification
- A riser specification
- A BS-material specification
- Load case specification (deflection angle and tension, i.e. the load case to analyze)
- FE-analysis parameters

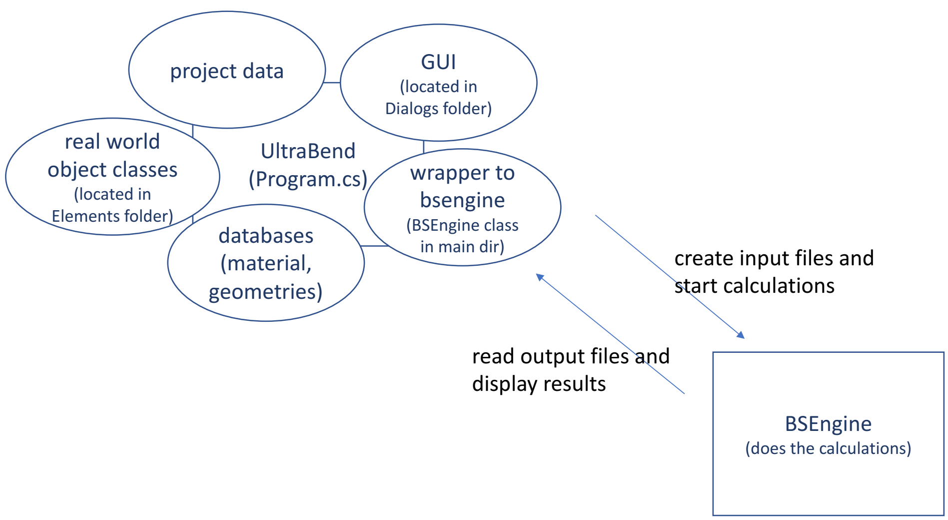
BS-engine performs the calculations and generates a text or binary (user specified) result file that contains (high-level):

1. Key results
2. Total number of elements and number of elements in bend stiffener
3. Bend stiffener results
4. Coordinates and curvature for the complete model
5. Element results for the complete model
6. Element results for the riser only

5.4 UltraBend

UltraBend already exists, but quite a bit of programming remains. The following is a description of some of the existing structure.

5.4.1 Current Structure



5.4.2 Databases

UltraBend currently has three databases:

1. Material Database
    a. The material database contains user-defined PU material properties, both linear (elastic modulus) and non-linear (stress/strain curves) at user-defined temperature levels.
2. Geometry Prototype Database
    a. Typically, a bend stiffener consists of combinations of cylindrical and conical segments. The prototype database can contain user-defined predetermined combinations of these segment types.
3. Geometry Database
    a. The geometry database contains previously designed bend stiffeners.

5.4.3 Input Data Interface Section

The UltraBend GUI currently has an input data interface section with the three following data section headings:

1. **SETTINGS** (BS-engine FE analysis related parameters)
    a. Iteration tolerance
    b. Maximum iterations
    c. Basic load increment
    d. Min. load increment
    e. Max. load increment
    f. Riser length outside BS
    g. No. of FE elements per meter
2. **DATA**
    a. **Riser/Umbilical** (geometric and mechanical data describing the riser along with the riser's mechanical capacity under "normal" and "abnormal" conditions)
        i. OD
        ii. Axial stiffness
        iii. Bending stiffness
        iv. Torsional stiffness
        v. Mass per unit length
        vi. Normal operation capacity curve (input of data points of the riser's allowable combinations of tension and curvature that leads to max allowable utilization)
        vii. Abnormal operation capacity curve (input of data points of the riser's allowable combinations of tension and curvature that leads to max allowable utilization)
    b. **Load Cases** (Design contours in terms of tension and deflection angles obtained from global analyses of the riser system under normal and abnormal conditions
        i. Normal Operation (deflection angles at various tension levels obtained from global analysis of the riser system under "normal" conditions)
        ii. Abnormal Operation (deflection angles at various tension levels obtained from global analysis of the riser system under "abnormal" conditions)
    c. **Material** (choice of PU material grade and temperature)
        i. Here the user can choose one or several material grades that analyses should be performed for along with the temperature(s) the analyses should be run at
3. **ANALYSIS**
    a. UltraBend shall have three modes of analysis:
        i. "Load Case Analysis"
        This is simply running of BS-engine with a known riser, a known BS, at known

load case(s) to obtain the BS’ performance at the given load case(s). UltraBend will present data as described later.

ii. “Find Optimal Bend Stiffener Geometry”
UltraBend shall run an optimization routine on several BS geometries. The routine shall be able to find the smallest BS that fulfills all performance requirements. The optimization may or may not include several material types.

iii. “Find Best Bend Stiffener from Set of Geometries”
UltraBend shall run all load cases for all identified BS geometries and identify which one(s) that fulfills all performance requirements. The analyses may or may not include several material types. This mode of analysis shall also be possible to run with only one geometry but several material types.

5.4.4 UltraBend’s Handling of BS-engine and BS-engine Licensing

Both UltraBend and BS-engine will need a valid license to operate. The way this is handled today is that both BS-engine and its license are part of UltraBend’s resources, and that these are unpacked when used and removed when UltraBend is no longer in use. This approach should be changed since subsequent upgrades of program licenses possibly would mean that a complete re-installation is necessary.

5.4.5 Detailed Description of UltraBend

Reference is made to [2].

6 CHALLENGES

- licensing of BS-engine
- how to handle (detect, solve) FE-analysis convergence issues
- efficient optimization routine
- multi threading
- potential licensing of UltraBend at different "number-of-features" level