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Bend stiffeners for flexible pipes: A comparative study between Attachment and Pipe-in-Pipe modeling

Ana Paula O. Benete[1], Bruno F. Monteiro[1], Carl H. Albrecht[1], Juliana S. Baioco[1], Breno P. Jacob[2], Marcelo Igor L. de Souza[1]

[1]*Poli/UFRJ – Polytechnic School of the Federal University of Rio de Janeiro*
Athos da Silveira Ramos, 149, CT, Cidade Universitária, Ilha do Fundão, 21941-909, Rio de Janeiro, RJ, Brazil
anaoliveira@poli.ufrj.br, bruno.monteiro@poli.ufrj.br, carl@poli.ufrj.br, jsbaioco@poli.ufrj.br, migor@lts.coppe.ufrj.br
[2]*PEC/COPPE/UFRJ – Civil Engineering Dept., Post-Graduate Institute of the Federal University of Rio de Janeiro.*
Avenida Pedro Calmon, S/N, Cidade Universitária, Ilha do Fundão, 21941-596, Rio de Janeiro, RJ, Brazil
breno@lamcso.coppe.ufrj.br

Abstract. This paper presents a comparative analysis between two modeling methodologies for bend stiffeners applied to subsea flexible pipes: the Attachment model and the Pipe-in-Pipe model. The main motivation lies in the need to ensure the structural integrity of pipelines during installation operations in offshore environments, especially in deep and ultra-deep waters, where dynamic loads are significant. A top riser deployment scenario was simulated under different environmental conditions and top angle presets of 1º, 3º, and 5º. The analysis focused on maximum top tension, top angle, shear force and bending moment of the stiffener, line curvature below the stiffener, and simulation runtime. Results show that both approaches yield similar global performance for top tension and angle, while the Pipe-in-Pipe model offers greater freedom of movement for the riser and shorter simulation times (on average 22% faster). However, this approach requires more detailed input data, especially regarding the definition of contact stiffness, which can cause convergence problems. It is possible to conclude that Attachment is preferable for early design stages or when frequent adjustments are needed, whereas Pipe-in-Pipe is recommended for consolidated projects demanding greater accuracy in representing stresses and relative motions.

Keywords: Offshore Systems, Installation Engineering, Flexible Pipes, Bend Stiffener.

1 Introduction

The increasing complexity of offshore operations in deep and ultra deep waters has driven the development of solutions that are both robust and efficient to ensure the structural integrity of subsea systems [1]. Among the various critical components, bend stiffeners [2] play a fundamental role in protecting the end regions of flexible pipes, especially during installation operations and under severe environmental conditions [3, 4]. Flexible pipes are subject to dynamic loads caused by currents and waves, as well as to high hydrostatic pressure and significant axial tensions during handling and lay operations. These combined effects concentrate at the end fittings and nearby transitions, where the risk of excessive curvature and fatigue damage is greatest.
For this reason, bend stiffeners, Fig. 1, are installed at the top and, when applicable, at intermediate connections to provide a gradual stiffness transition between rigid hardware and the flexible pipe body. In practice, installation vessels such as PLSVs – Pipelay Support Vessel [5] impose the most demanding load states during launch and pull in, and the top region is where the largest curvatures and interface forces tend to occur. Numerical simulation in time domain using finite elements has therefore become a standard practice to predict structural response and

check integrity criteria during installation planning [1, 3, 6, 7].
This work comes from an undergraduate thesis of Naval, Oceanic and Coastal Engineering course at UFRJ and it deepens the comparative analysis between two modeling methodologies for bend stiffeners molded in OrcaFlex software: the Attachment model and the Pipe in Pipe model. The Attachment model represents the stiffener as a homogeneous sleeve directly attached to the line, typically assuming no relative motion and equal curvature between sleeve and pipe. The Pipe in Pipe model represents the stiffener as a separate outer line interacting with the riser through contact, enabling relative motion and a more realistic transmission of local loads. Through a representative top riser deployment scenario from a PLSV, global responses were evaluated (top tension and top angle), local effects (shear and bending at the stiffener base, curvature just below the stiffener), and computational performance (runtime). The goal is to provide technical guidance for selecting the most suitable approach according to project phase and data availability, balancing conservatism, fidelity, and efficiency.

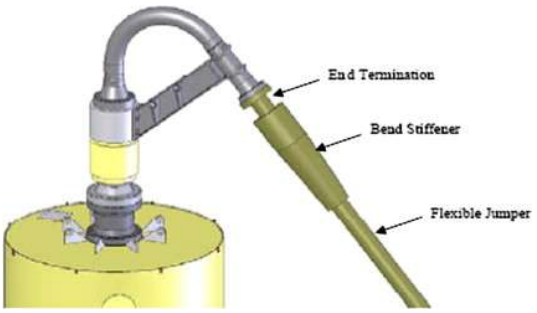


Figure 1. Bending Stiffener [9]

2 Objectives and scope

This study aims to conduct a comparative analysis between two modeling methodologies for bend stiffeners applied to subsea flexible pipes: the Attachment model and the Pipe-in-Pipe model, using OrcaFlex. The adopted methodology involved simulating a top riser deployment scenario under regular waves and a realistic current profile, considering three preset static top angles of 1º, 3º, and 5º [8]. Parameters analyzed include maximum top tension and top angle, shear force and bending moment at the base of the stiffener, curvature of the line below the stiffener, and total simulation runtime. The analysis seeks to inform when each modeling approach is most appropriate: early stages and frequent changes favor Attachment model; consolidated phases requiring higher local fidelity favor Pipe-in-Pipe model.

3 Methodology and Case Study Description

The analysis is based on a time domain finite element formulation as implemented in OrcaFlex [7]. The flexible pipe is discretized into nodes connected by axial and torsional elements, with bending represented by rotational springs and dampers at segment ends. Hydrodynamic forces, added mass, and drag are accounted for, and vessel motions are imposed via RAOs. A static analysis is first performed to obtain equilibrium with endpoints fixed and then released to resolve residual imbalances, followed by dynamic simulations comprising a buildup stage and two subsequent stages that together span four wave periods.
The system represents a PLSV vertical lay arrangement with the riser top segment supported on the worktable and the stiffener mounted at the upper end fitting. The water depth is 1400 m, representing deep water conditions. The seabed is modeled as a flat plane with linear springs in normal and tangential directions, representing very soft sand with normal and shear stiffness and also representative friction coefficients are described in Tab. 1. The vessel has six degrees of freedom (surge, sway, heave, roll, pitch, yaw), with motions prescribed through RAOs to reflect the frequency dependent response under regular waves. Its other parameters are presented in Tab. 2.
The main properties of the flexible pipe are shown in Tab. 3. Accessories at the top include the end fitting, a rigid stiffener section, and a conical section, each with its own geometry and mass properties, which are described in Tab 4. Regular waves are modeled with 5th order Stokes theory, with different vessel incidence degrees. Wave

parameters can be seen in Tab. 5 and the schematic view of wave incidence on the PLSV is shown in Fig. 2. The current profile varies with depth and direction, with the top current aligned with the line heading to represent a worst case for the top region. The parameters of current profile are presented in Tab. 6.

Table 1. Seabed properties

Parameter	Value / Description
Normal stiffness	100 kN/m/m² (very soft sand)
Shear stiffness	10,000 kN/m/m²
Normal friction coefficient	1.07
Axial friction coefficient	0.35

Table 2. PLSV characteristics

Parameter	Value / Description
Draft	7.13 m
LCG (from midship)	2.76 m
TCG (from longitudinal axis)	0.00 m
VCG (from baseline)	4.51 m
Vessel motions	RAOs

Table 3. Flexible riser properties

Parameter	Value
Outer diameter	0.195 m
Inner diameter	0.102 m
Submerged unit weight (water-filled)	52.68 kgf/m
Bending stiffness	11.83 kN·m²
Axial stiffness	5.47×10^5 kN
Torsional stiffness	758 kN·m
Damaging pull	3432.33 kN

Table 4. Top accessories characteristics

Parameter	Value
End fitting length	2124 mm
End fitting submerged weight	1107 kgf
Stiffener (rigid section) length	3165 mm
Stiffener (rigid section) diameter	1000 mm
Stiffener (conical section) length	4590 mm
Stiffener (conical section) outer diameter	1209 mm
Stiffener (conical section) inner diameter	203 mm
Stiffener (conical section) submerged weight	199.5 kgf

Table 5. Wave conditions

Parameter	Value / Description
Significant wave height (Hs)	4 m
Peak periods (Tp)	6 s to 15 s
Headings	See Fig. 2
Wave theory	5th-order Stokes

Table 6. Current profile

Parameter	Value / Description
Type	Layered, depth-varying, with directional veer
Surface current speed	1.24 m/s
Bottom current speed	0.12 m/s
Surface current direction	Aligned with riser heading (worst case)

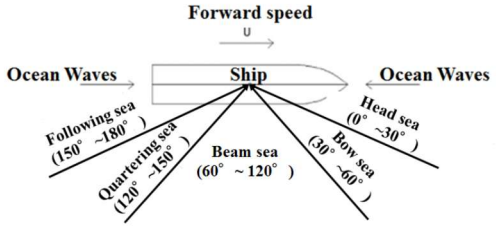


Figure 2. Schematic view of wave incidence on the model [10]

Riser discretization is refined near the top and near the touchdown point to capture curvature gradients, while mid span elements are longer to keep computational cost reasonable. In the Attachment approach, the conical sleeve is modeled as a homogeneous pipe attached to the riser at the z position corresponding to the start of the protected length, with either concentrated or distributed load transfer along the stiffener. This approach constrains relative motion and tends to be conservative in curvature near the base because it assumes equal curvature for stiffener and pipe. In the Pipe in Pipe approach, the stiffener is modeled as a separate outer "spline" line, and the riser is the penetrating line with nodal penetrators. The critical input is the contact stiffness (normal and tangential), which governs penetration and numerical stability. Accurately defining this stiffness improves realism but can challenge convergence if set unrealistically high. Following, Fig. 3 shows the riser discretization while Fig. 4 shows the bend stiffener discretization.
Since it involves the application of regular waves, each dynamic simulation lasts the time necessary for two periods of the acting wave to be observed.

Sections: 18 Total length = 1887,61m

No.	Line type	Section length (m)	Expansion factor	Target segment length (m)	Number of segments
1	Conector	2,124	~	~	1
2	Enrijecedor_ParteRígida	3,165	~	~	5
3	Riser_Alagado	4,59	~	0,459	10
4	Riser_Alagado	1,0	~	1,0	1
5	Riser_Alagado	1,45	~	1,45	1
6	Riser_Alagado	2,102	~	2,102	1
7	Riser_Alagado	3,049	~	3,049	1
8	Riser_Alagado	4,421	~	4,421	1
9	Riser_Alagado	6,41	~	6,41	1
10	Riser_Alagado	9,294	~	9,294	1
11	Riser_Alagado	100,0	~	15,0	7
12	Riser_Alagado	800,0	~	30,0	27
13	Riser_Alagado	400,0	~	10,0	40
14	Riser_Alagado	50,0	~	5,0	10

Figure 3. Riser discretization – Orcaflex screen

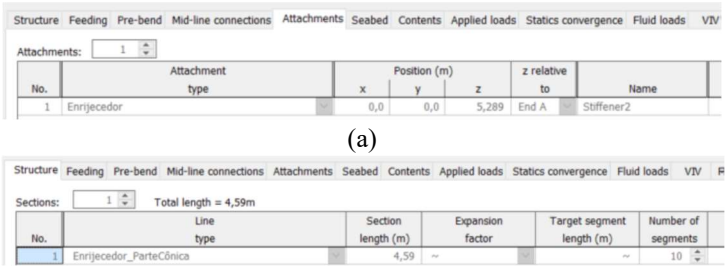


Figure 4. Bend stiffener discretization, (a) Attachment and (b) Pipe-in-pipe – Orcaflex screen

4 Results and discussion

The simulations compare the two modeling approaches across the three preset top angles of 1º, 3º, 5º and across wave headings. For each case, peak values are extracted after the buildup stage over two wave periods. The focus is on the interaction between global and local responses and on the practical implications for installation process.
Global responses of maximum top tension and maximum top angle, see Tab. 7, were essentially identical between Attachment and Pipe in Pipe for all headings and top angles. Differences in top tension were within 0.35%, and top angle differences were typically within about 1%. This behavior indicates that global axial loading and inboard geometry are dominated by the system mass, hydrodynamic loading, and vessel motions, with negligible sensitivity to the local stiffener modeling assumption at this scale. In practice, either model is appropriate to verify compliance with allowable installation pulls and top angle envelopes.
In contrast to this, local responses at the stiffener base as shear force and bending moment evaluated at the first node of the conical section revealed meaningful differences. From Tab. 8, one can note that the Attachment model produced higher shear and bending forces, with Pipe in Pipe yielding reductions of approximately 18% to 28% in shear and around 4% to 12% in bending, depending on heading and top angle. These trends are consistent with the underlying assumptions: Attachment model suppresses relative motion and concentrates demand near the base, while Pipe in Pipe model allows some redistribution through contact and relative sliding, producing more natural load sharing.
Curvature distributions in the first meters below the stiffener further highlight this difference. In both models, a stiffness transition is observed at the rigid-flexible interface near the stiffener base. In the Pipe-in-Pipe model, this transition is more abrupt at the onset but then decreases progressively along the pipe. In contrast, the Attachment model maintains a higher curvature concentrated near the base over a shorter distance, as a result of the imposed constraint. This distinction is relevant for cases where curvature-driven criteria or wear mechanisms are critical, as the Pipe-in-Pipe approach may more accurately capture the physical behavior at the stiffener-pipe interface. It's important to point out that in both cases curvatures keep within allowable values [1, 6].
Regarding computational performance, Tab. 9, it was chosen only the wave (incidence direction with all peak periods) that produced the most extreme results, that is, Hs = 4 m and incidence beam sea. Pipe-in-Pipe simulations were, on average, 22% faster than the Attachment model for beam sea cases with wave periods between 6 and 15 s, although some variation was observed for the shortest periods. Despite the additional contact calculations required, the overall system stiffness and time-integration characteristics of the Pipe-in-Pipe approach resulted in shorter runtimes for the tested configurations. In larger-scale models involving multiple lines and vessels, this efficiency gain could translate into significant reductions in processing time.

Table 7. Global responses: maximum top tension and maximum top angle for both models across headings and top angle presets

Top angle preset	Sea state heading	Max top tension (kN) Attachment	Max top tension (kN) Pipe in Pipe	Relative diff. (%)	Max top angle (°) Attachment	Max top angle (°) Pipe in Pipe	Relative diff. (%)
1°	Head seas	943.00	943.00	0.00	6.5	6.4	−0.91
	Bow seas	968.00	968.00	0.03	9.6	9.5	−1.10
	Beam seas	1139.00	1140.00	0.07	8.5	8.5	−0.81
	Quartering seas	957.00	957.00	−0.01	9.1	9.0	−1.08
	Following seas	948.00	948.00	0.00	6.5	6.4	−0.86
3°	Head seas	975.00	975.00	−0.01	8.0	7.9	−0.46
	Bow seas	1007.00	1008.00	0.09	11.3	11.2	−0.79
	Beam seas	1170.00	1174.00	0.35	10.7	10.6	−0.42
	Quartering seas	992.00	992.00	0.05	10.8	10.7	−0.76
	Following seas	981.00	982.00	0.05	7.9	7.9	−0.43
5°	Head seas	1011.00	1012.00	0.06	9.6	9.5	−0.30
	Bow seas	1055.00	1055.00	0.02	13.0	12.9	−0.65
	Beam seas	1294.00	1297.00	0.24	12.8	12.8	−0.32
	Quartering seas	1038.00	1038.00	0.02	12.5	12.5	−0.61
	Following seas	1019.00	1019.00	0.05	9.6	9.5	−0.28

Table 8. Global responses: maximum shear force and maximum bending moment for both models across headings and top angle presets

Top angle preset	Sea state heading	Attachment (kN)	Pipe-in-pipe (kN)	Relative discrepancy (%)	Attachment (kN.m)	Pipe-in-pipe (kN.m)	Relative discrepancy (%)
1°	Head seas	11.07	8.00	-27.71	46.75	41.61	-10.99
	Bow seas	11.90	9.23	-22.44	61.37	55.20	-10.04
	Beam seas	12.11	12.87	6.28	21.58	20.38	-5.54
	Quartering seas	11.77	9.10	-22.70	59.32	53.37	-10.03
	Following seas	10.97	8.00	-27.03	46.39	41.25	-11.07
3°	Head seas	11.17	8.64	-22.67	46.06	40.85	-11.31
	Bow seas	11.22	10.27	-8.52	59.18	52.93	-10.56
	Beam seas	13.34	13.81	3.57	24.82	23.60	-4.94
	Quartering seas	11.13	10.14	-8.88	57.20	51.20	-10.48
	Following seas	11.06	8.64	-21.93	45.69	40.49	-11.39
5°	Head seas	11.37	9.32	-18.04	45.42	40.15	-11.61
	Bow seas	10.61	11.34	6.97	57.03	50.74	-11.04
	Beam seas	14.61	14.98	2.53	29.97	28.80	-3.90
	Quartering seas	10.55	11.20	6.21	55.03	48.98	-10.98
	Following seas	11.27	9.33	-17.22	45.06	39.79	-11.69

5 Conclusions

This study compared Attachment and Pipe in Pipe modeling approaches for bend stiffeners in flexible risers under a representative top deployment scenario. Both approaches produced very similar global responses in terms of maximum top tension and top angle, suggesting that either is adequate for global installation checks and interface envelopes. However, local responses at the stiffener base were consistently higher with Attachment, reflecting its conservative constraint that enforces equal curvature and suppresses relative motion. Pipe in Pipe reduced shear and bending peaks and provided smoother curvature distributions, better capturing the physical stiffness transition at the sleeve interface. In addition, Pipe in Pipe delivered shorter runtimes on average (about 22% faster), which can provide practical efficiency gains at project scale.

We conclude that the Attachment model is more suitable for early project stages or when frequent model adjustments are needed, as it is simpler and more robust to changes, even if conservative. The Pipe in Pipe model is recommended for consolidated phases that demand higher fidelity in representing local stresses, curvatures, and relative movements, provided that contact stiffness is well characterized from supplier data or calibrated studies. The choice between methods should balance the need for speed and simplicity against the benefits of local realism and accuracy.

Table 9. Simulation runtime comparison (beam seas, Hs = 4 m): Attachment vs. Pipe in Pipe across wave periods for 1º, 3º, and 5º top angle presets

Top Angle Preset	Tp (s)	Runtime (s) Attachment	Runtime (s) Pipe-in-Pipe	Relative diff. (%)
1º	6	36.6	28.6	−22
	7	41.1	32.4	−21
	8	46.5	36.1	−22
	9	52.4	39.0	−26
	10	58.2	44.1	−24
	11	59.6	48.1	−19
	12	68.7	51.8	−25
	13	73.5	56.9	−23
	14	80.0	60.3	−25
	15	85.8	63.7	−26
3º	6	37.5	29.8	−20
	7	41.9	33.8	−19
	8	48.1	37.2	−23
	9	45.2	41.6	−8
	10	49.5	43.7	−12
	11	54.0	41.7	−23
	12	70.9	52.5	−26
	13	73.2	56.3	−23
	14	79.7	61.5	−23
	15	85.1	65.4	−23
5º	6	31.5	28.8	−8
	7	35.6	32.8	−8
	8	47.9	37.0	−23
	9	53.5	40.6	−24
	10	58.9	43.8	−26
	11	62.8	48.6	−23
	12	69.1	51.8	−25
	13	74.5	55.0	−26
	14	82.8	59.7	−28
	15	87.5	63.0	−28

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