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# Bend stiffener nonlinear viscoelastic time domain formulation

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ABSTRACT

Bend stiffeners are conical polyurethane structures used in the offshore industry to ensure a smooth transition in the upper connection of flexible risers with the floating production unit. The polyurethane employed for bend stiffeners present a nonlinear viscoelastic response that is highly dependent on the loading rate and temperature. This may lead to different flexible riser response when compared to elastic or hyperelastic material modeling. In order to quantify this effect, tensile and relaxation tests are carried out to characterize the nonlinear time dependent mechanical behavior of the polyurethane. A constitutive equation based on the modified superposition method is then presented and a procedure for material identification proposed. A numerical scheme using the state variable approach is formulated for the nonlinear viscoelastic constitutive equation finite element implementation. The top connection system, consisting of a bend stiffener and a flexible pipe segment, is represented by a large displacement beam model accounting for geometrical and material nonlinearities. A case study is carried out to compare the system curvature response calculated for the nonlinear viscoelastic and hyperelastic (Marlow strain energy potential) bend stiffener subjected to harmonic loading conditions at different frequencies. The results show the importance of bend stiffener strain rate dependency on the riser curvature response.



## 1. Introduction

Flexible pipes and umbilical cables have been used in subsea production systems since 1970s and nowadays a great part of the Brazilian offshore oil and gas production makes use of these structures. The growing demand for this product and the challenges related to deeper water operations is increasingly requiring better knowledge of the possible failure modes for the pipe itself and for ancillary components. The flexible pipe top connection with the platform is a critical point regarding the maximum allowed curvature and fatigue life, as this region is susceptible to the highest forces and curvatures due to stochastic loading conditions. In order to prevent the riser failure from over bending, which may cause unlocking of the pressure armour layer, and from accumulation of fatigue damage, a sound controlled stiffness transition between the dynamic flexible pipe and the stiff hung-off area is required. An effective way to achieve this is the use of a conical shaped structure made of polyurethane called bend stiffener.

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The dynamic behavior of a flexible riser system with a bend stiffener can be investigated by a complete global dynamic model using beam elements with varying stiffness to represent the polyurethane cross section variation along its length. This model is useful for verification purposes, but may lead to a very slow iterative design process as, in principle, many bend stiffener geometries should be evaluated to achieve the optimum one. Another drawback is that most of the commercially available global dynamic software's do not allow an accurate modeling of the polyurethane material nonlinearities. As shown by Sodahl and Larsen [1], the global behavior of the system is highly influenced by dynamic effects, but the bend stiffener response is locally dominated by quasi-static effects and consequently the analysis can be carried out in separate models as shown in Fig. 1. The approach traditionally adopted is to perform the dynamic global analysis for each stationary short term environmental condition, removing the stiffener and only considering flexible riser elements in this section. The input loading conditions for the bend stiffener should then be defined in terms of effective tension and relative angle time series and used as input to *the intermediate quasi-static model*. This kind of procedure reduces the need for dynamic simulations to a minimum in the bend stiffener design process.

For extreme loading conditions, the design has to ensure that the flexible riser does not bend below the allowable minimum bending radius (MBR), usually determined from a maximum allowed bending strain in the flexible pipe outer sheath (e.g. 7%). The bend stiffener polyurethane surface maximum strain is another parameter usually adopted as a dimensioning parameter. As pointed out by Smith [2], the stiffener design for extreme loading normally proves to be acceptable for less onerous fatigue loading provided the steel armours in riser annulus stay dry.

A similar methodology can be applied for the long term lifetime integrity assessment of the flexible riser at top connection. In that case, a stress transfer function is generally adopted to obtain the tensile armour stresses and strains from the tension and curvature of a given riser section located along the intermediate model length, as described by Doynov et al. [3] and Sousa et al. [4]. This is done due to the high computational cost of a detailed flexible riser finite element analysis that, otherwise, would be required for each short term environmental condition. An overview of finite element formulations for assessment of tensile armour stresses is presented by Saevik [5]. Fig. 2 illustrates this procedure.

The intermediate model for analysis and design of bend stiffeners is usually represented by a large displacement and rotation beam model. This approach has been employed by Boef and Out [6] considering the large deflection of slender rods with a linear elastic polyurethane. They compared the model with a three dimensional finite element analysis and concluded that the analytical method is a reliable tool for design. Lane et al. [7] pointed out that a three-dimensional finite element analysis might be required for assessment of stress concentration points, such as, the interface between the metallic interface and the polyurethane.

Caire and Vaz [8] presented an extension of the linear elastic beam model to include the effect of nonlinear flexible pipe bending moment x curvature response on the system behavior. The effect of the gap between the structures was also evaluated by a finite element model and they concluded that for fatigue analysis both considerations are important. In a more recent work, Caire [9] has investigated an equivalent elasto-plastic formulation, where a hardening parameter controls the

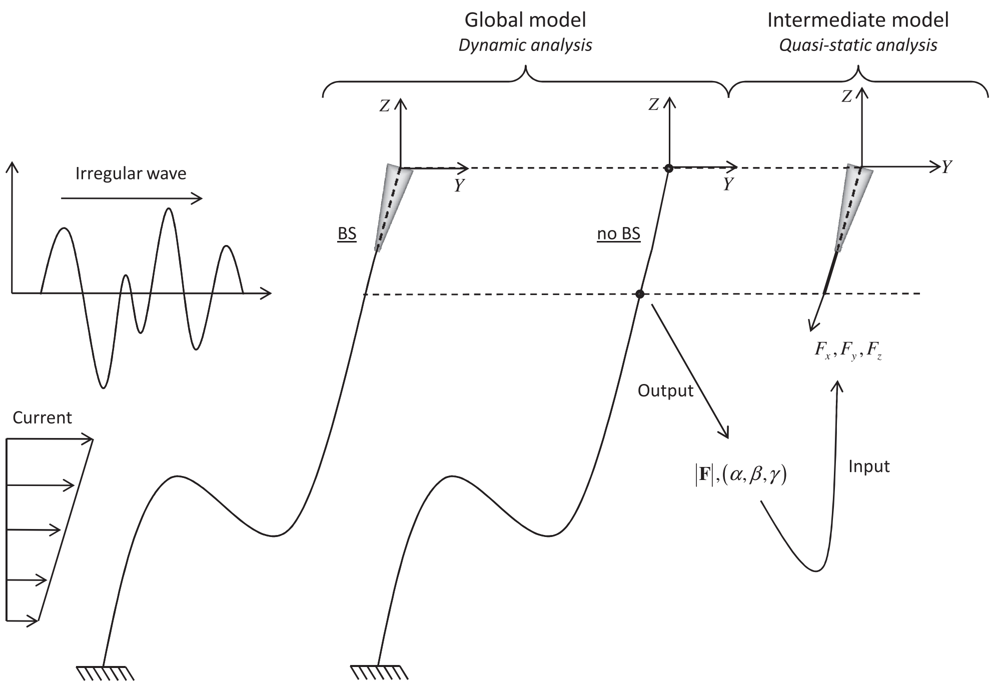


**Fig. 1.** Bend stiffener analyses methodologies.