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FLEXIBLE RISER BENDING HYSTERESIS INFLUENCE ON BEND STIFFENER RESPONSE

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ABSTRACT

The bending stiffness response is an important parameter in the lifetime assessment of unbounded flexible risers. Its behavior is governed by interlayer friction mechanisms leading to a non-linear moment x curvature relationship that is highly dependent on the internal pressure. In order to investigate its influence on the critical bend stiffener hang-off region response, a detailed finite element analysis is carried out using a specialized tool for a short segment length of a selected 2.5" ID riser cross section. Different internal pressures are numerically analyzed and the resulting local hysteretic bending response is then adjusted and directly incorporated into a global dynamic analysis tool that uses an equivalent elasto-plastic formulation with a hardening parameter that controls the behavior of the slippage mechanism. A fully coupled irregular wave dynamic analysis is then carried out and the flexible riser curvature distribution response in the bend stiffener region compared for different bending hysteresis models adopted.

INTRODUCTION

Flexible riser systems are increasingly being employed in ultra deepwater environments where a cost-effective solution is essential for field development. In this scenario, the structural design and lifetime evaluation methodologies become critical factors as the accepted conservatism shall be gradually decreased. Accurate prediction requires an efficient method capable of incorporating detailed flexible riser models into a global nonlinear dynamic analysis. The current industry practice is a two-step global/local approach involving global nonlinear analysis models, which may include bending hysteresis effects, followed by local analysis of a detailed model segment for lifetime assessment. An overview of this methodology can be found in Sousa *et al.* [1]

As pointed out by Caire and Schiller [2], the modeling simplifications and assumptions adopted in the global dynamic analysis usually increase the analysis conservatism. They have investigated the effect of wind-wave energy spreading acting on a FPSO-riser-mooring system using a fully coupled dynamic analysis approach. This takes the inertial and damping forces (which may include the bending hysteresis and plastic layers viscoelasticity) of the submerged risers and moorings into account in the vessel response and intrinsically considers the vessel heading and offset variation for each time step.

For the riser bending stiffness parameter used as input to the non-linear global dynamic analysis, a conservative approach is often adopted in the industry practice as mentioned by Smith *et al.* [3]. The approach is to use the relatively small bending stiffness value corresponding to full sliding of the armour layers. However, the interlayer friction between the tensile armor layers causes a highly damped non-linear bending response which increases with internal pressure and friction coefficient. In their work, they presented the bending hysteresis model that has been implemented in the FLEXCOM analysis tool and two case studies: a two dimensional catenary riser hanging from a FPSO and a three-dimensional steep-wave riser deployed in shallow water. The main observation is that the hysteresis model help reducing the maximum curvature distribution in the touchdown zone and in the riser hang-off area.

By using a similar approach, Tan *et al*. [4] describes the flexible riser bending hysteresis models implemented in the global analysis program ORCAFLEX and the coupling to a Wellstream detailed local model to compute armor stresses in a feed-back loop fashion. For each time-step, global analysis curvatures are input into the local model which then proceeds to calculate the tensile wire stresses and bending moments. In a case study of a turret FPSO with a free hanging catenary riser configuration they model a section around the touchdown zone and show that the bending moment hysteresis model considerable reduces the curvature amplitude when compared to the linear stiffness model.

Caire and Vaz [5] presented a simplified mathematical formulation and numerical solution to represent the riser/bend stiffener system at top connection as a two dimensional beam model considering bi-linear moment curvature relationship for the pipe. They have also evaluated the effect of gap between the structures using a finite element model. Although the model did not incorporate the damping effect in cyclic loading due to interlayer friction, they have observed that both the bi-linearity and the gap may give somewhat less conservative results for fatigue loading conditions. A non-linear viscoelastic formulation for the bend stiffener has been later presented by Caire [6] who has shown that even though the polyurethane damping does not significantly affect the top-connection system response, the non-linear viscoelastic rate dependent response of the bend stiffener has a big impact on the riser curvature response in this critical region.

As described by the above mentioned authors, this amplitude dependent type of damping may help decreasing the dynamic analysis conservatism in critical areas, such as, the touchdown zone and riser hang-off. In the present paper a 2.5" flexible riser cross section is employed in a detailed finite element analysis (BFLEX 2010 [7]) to numerically obtain the hysteretic response for different internal pressures. The numerically calculated hysteretic moment-curvature relation is then adjusted and directly used as input for a fully coupled global dynamic analysis (RIFLEX [8] and SIMO [9]) of a typical spread-moored FPSO operating offshore Brazil in a water depth of approximately 1250m subjected to multidirectional wave conditions. The bend stiffener is included in the global model and the riser curvature distribution response is then compared for the different bending hysteresis models adopted in the hang-off region. A three dimensional beam example is also presented for finite element material modeling comparison purposes.

FLEXIBLE RISER BENDING HYSTERESIS RESPONSE

The hysteresis in the bending moment effectively acts as a damper, dissipating energy. It originates from the friction between the different layers of the riser. Up to a certain curvature (critical curvature), the friction is able to prevent slip between layers and with increasing bending moment, slippage starts gradually until full slip of the layers occurs. After load reversal, the friction acts in the opposite direction and thus resulting in a hysteresis effect.

Local finite element modeling

The finite element based computer program BFLEX 2010 is used for the local cross section analyses of a selected riser in the case study. It is a tool for stress analysis of tensile armours in flexible pipes exposed to pressure, tension and bending loads. The tensile armour is based on two different formulations: i) a sandwich beam formulation (SBM) where the equilibrium equations for the tendons and supporting beam structure are solved and ii) a moment formulation (MM) where the equilibrium equations are established based on a friction moment approach. More information on the modeling methodology can be found on the work by Saevik [10].

As pointed out by Saevik [10], the tendons are in the stick regime for small curvatures where the bending stiffness is close to a steel pipe of similar dimensions. After slip, the bending stiffness is governed by the plastic layers and the elastic bending contribution from each individual armour tendon, until the initial gaps between armour tendons are closed and the stiffness again increases until pipe failure.

As described in the program theory manual, in order to minimize the number of degrees of freedom and to obtain numerical stability, the transverse slip of the tensile armour is neglected, i.e. the tensile armour is assumed to follow a loxodromic surface curve as shown in Fig. 2.1. This is a reasonable assumption for realistic friction coefficients and the sensitivity of this assumption with regard to predicting the curvature and tensile armour axial stress distribution is considered small. It is additionally assumed that the cross-section maintain it's form sufficiently to allow all local bending and torsion effects of the tensile armour to be calculated analytically. Shear stresses between armour tendons and supporting layers only occur as a result of bending and hence axisymmetric strains and bending strains are assumed uncoupled.

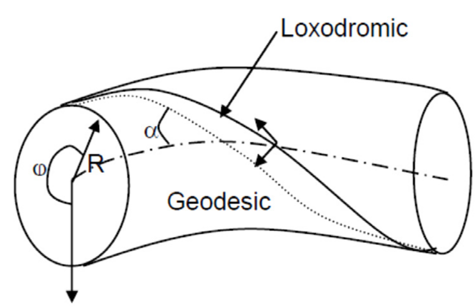

Figure 2.1 – Loxodromic and geodesic helical path along bent cylinder [7]

The public available experimental data of the 2.5" ID flexible pipe cross section published by Witz [11] has been selected for the case study. The paper presents a comparison between the numerical results of 10 different institutions with the experimental data of a Coflexip flexible riser design. By that time it was clear that more attention should been given to the structural response under combined axial, torsional and bending loading (some uncertainties still remains) while axisymmetric results agreed reasonable well.

The geometric and material properties of each layer can be found in [11], with the exception of the friction coefficient between layers that is not provided. The bending moment x curvature for a 300 bar internal pressure experimental test can be seen in Fig. A.1

In the present case study the riser cross section has been modeled in BFLEX 2010 considering a 1 meter pipe segment. The moment based model (MM) formulation has been selected, which means that one moment-curvature is created for each layer, taking into account the slip property of each.

In order to assess the effect of internal pressure in the local finite element model, 2 values are selected for numerical analysis (100 and 300 bar). The interlayer friction coefficient is kept the same (f=0.15) in all layers for the different internal pressures. The results can be seen in Fig. A.2 and it can be observed, as expected, that the higher the internal pressure the higher the dissipated energy per cycle due to increased friction forces.

Global hysteretic behavior modeling

In the special purpose global dynamic analysis tool RIFLEX, it is possible to specify a non-linear hysteretic bending moment x curvature relationship in tabular form. The modeling is based on an equivalent *elasto-plastic formulation* where a hardening parameter controls the behavior of the yield surface. Kinematic hardening is specified by a hardening parameter equal to 1.0 and isotropic hardening (elastic range is extended as function of curvature experienced by the pipe) is specified by a parameter equal to 0.0. The isotropic hardening leads to larger elastic region, on reverse loading, when compared to the kinematic rule where the yield surface translates in bending moment space rather than expanding.

Figure A.1 shows the RIFLEX data fitting (using the hysteretic bending model with kinematic hardening rule) of the experimental data presented by Witz [11] when the riser was subjected to an internal pressure of 300 bar. The results show excellent agreement. In Fig. A.2 the RIFLEX fitting of the numerically calculated bending moment x curvature using BFLEX for two values of internal pressure is also presented. It can be observed that the RIFLEX elasto-plastic approach for hysteretic bending modeling was able to provide a very good fitting of both the experimental data available and the numerical response calculated by BFLEX for the two dimensional case.

The general purpose finite element package ABAQUS [12] is also employed in the case study for material modeling comparison purposes. A 2-node linear beam in space has been selected (B31) associated with a thin-walled pipe section and a linear kinematic hardening model. The beam section is integrated during the analysis (8 integration points along circumference), recomputing the properties as the pipe deforms. As can be observed from Fig. A.1-6 the RIFLEX response agrees very well.

Three dimensional hysteretic bending model comparison

For the integrity assessment of flexible risers, the response models adopted by the global dynamic analysis tools need to handle three dimensional bending in a proper manner. Although it is straightforward for the linear bending stiffness case, when hysteresis is included, some uncertainties remain.

As public three dimensional experimental data is not available, a controlled numerical experiment is carried out in order to compare flexible riser bending response obtained by BFLEX and the equivalent elasto-plastic formulation adopted by the global tool RIFLEX and ABAQUS using two dimensional response data for model fitting.

A one meter segment pipe is subjected to harmonic tip loading in two directions (out of phase), leading to a circular movement in one end. Figures A.3 and A.4 show the bending moment and curvature, respectively, for the local Y and Z pipe encastre. Figures A.5 and A.6 show the bending moment x curvature history for a loading cycle. A good correlation can be observed between the three dimensional numerically calculated bending moment x curvature response and the global tool modeling approach using two dimensional data for fitting.

BEND STIFFENER POLYURETHANE RESPONSE

As presented by Caire [6], it's observed that the polyurethane employed for bend stiffeners is highly dependent on the loading rate and temperature (nonlinear viscoelastic behavior). The material response used in the present case study was obtained by tensile tests carried out for three different loading rates at room temperature with a typical class of polyurethane used for bend stiffeners. The tensile stress x strain response can be observed in the Fig. 3.1 below.

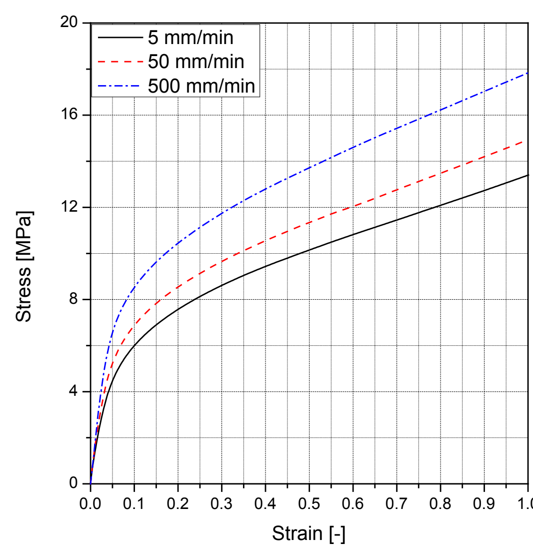

Figure 3.1 – Bend stiffener polyurethane stress x strain curve

The following table presents the secant modulus calculated considering 1, 2.5 and 5% strain for three different loading rates. A difference of about 45% can be observed, for example, from the modulus calculated at 5% strain for 5 and 500 mm/min. The choice of a representative elastic modulus is, consequently, not evident. The most accurate way of representing its response is by using a nonlinear viscoelastic constitutive equation, which intrinsically takes into account the nonlinear loading rate dependent response.

In the current version of RIFLEX it is possible to model the nonlinear stress x strain behavior but it does not allow modeling of nonlinear viscoelastic response. For simplification purposes, in the case study presented here, the bend stiffener secant modulus value has been selected as 129.8 MPa.

Table 3.1 – Polyurethane secant modulus

Loading rate [mm/min]	***Secant modulus [MPa]***		
	1.0%	2.5%	5.0%
5	131.4	113.1	89.3
50	155.4	133.2	104.2
500	191.9	165.0	*129.8*

FULLY COUPLED IRREGULAR WAVE DYNAMIC ANALYSIS OF TOP CONNECTION

FPSO-riser/bend stiffener-mooring system

The case study is carried out considering the same floating unit and mooring-riser system adopted by Caire and Schiller [2]. It consists of a spread-moored FPSO anchored with 20 mooring lines and 15 risers connected to port side, leaving starboard side free. The environmental conditions adopted in this study are representative of typical sea states from Santos Basin, offshore Brazil. For the multidirectional wave system, a SW direction is selected to represent swell and a SE direction is selected for wind waves. More details can be found in Caire and Schiller [2]

Case study description and results

For each flexible riser bending response (EI linear, hysteresis for P=100 and 300 bar), a 10min fully coupled time domain simulation were performed using the software SIMO and RIFLEX with the multidirectional wave system previously described. For the linear case the 10 min dynamic simulation has taken approximately 3 min of computational time, while for the hysteresis cases 5 min were required in a laptop computer with a time step of 0.1 sec for both.

The modeling methodology employed was to use a detailed beam mesh (0.01m segment length) for a 3m segment of the riser with hysteresis, where the bend stiffener has been modeled, and a rough bar mesh for the mooring line system and the other risers with linear stiffness. This allows the coupling effects to be taken into account in a proper way without heavily increasing the computational cost.

The Fig. A.7 and A.8 show the stochastic curvature time series (100 sec selection) for the local Y and Z axis of the flexible riser near the hang-off region. In the table below, the mean and the standard deviation is presented using the whole time series. It can be observed, for example, that the standard deviation is reduced by about 19% when comparing the full slip bending stiffness with the hysteresis model with 300 bars of internal pressure for both axis directions. Figures A.9 and A.10 show the bending moment x curvature history of the selected time series interval (100 sec) for local Y and Z axis respectively.

Table 4.1 – Curvature mean and standard deviation

Bending model	***Y axis***		***Z axis***	
	Mean	***Std. dev***	***Mean***	***Std. dev***
EI linear	0.1208	0.0080	0.0112	0.0087
P=100 bar	0.1216	0.0074	0.0112	0.0082
P=300 bar	0.1231	0.0065	0.0110	0.0072

SUMMARY AND CONCLUSIONS

A detailed local finite element analysis of a selected riser cross section is performed considering different internal pressures to evaluate its effect in the hysteretic bending response. The bending responses are adjusted employing an equivalent elasto-plastic approach and directly incorporated in the global dynamic analysis. A fully coupled irregular wave dynamic analysis with multidirectional wave environment is then carried out and the flexible riser curvature distribution response in the bend stiffener region compared for the different bending hysteresis models adopted. Experimental tensile tests are carried out with typical bend stiffener polyurethane samples for different loading rates. The numerically calculated three dimensional bending response is also compared with the specialized tool RIFLEX and the general purpose FE tool ABAQUS using two dimensional data for fitting. The main conclusions are as follows:

- Presently, state-of-art global and local analysis tools does not allow modeling of the experimentally observed rate-dependent (nonlinear viscoelasticity) behavior of bend stiffeners.
- The equivalent elasto-plastic approach implemented in RIFLEX has presented a very good fitting of both experimental and numerically calculated flexible riser bending hysteresis response.
- The higher the energy dissipated in a loading cycle due do flexible riser bending the lower will be the curvature amplitude response and standard deviation at hang-off. This help decreasing the lifetime assessment conservatism in this critical area of the riser.

ACKNOWLEDGMENTS

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[12] ABAQUS v6.13, 2013, Program documentation.

ANNEX A

CASE STUDY RESULTS

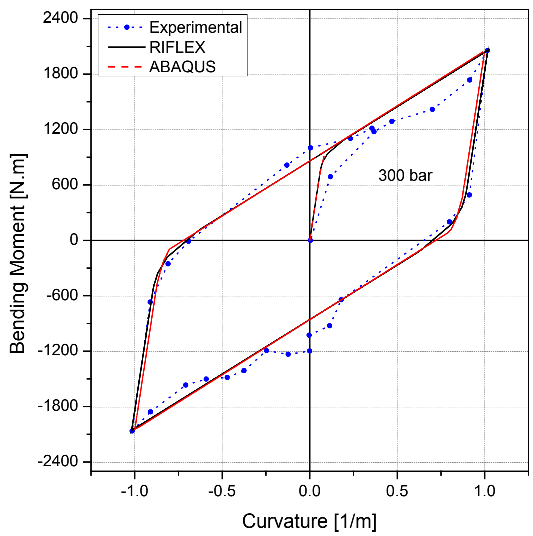

Figure A.1 – Experimental bending moment x curvature response comparison with RIFLEX and ABAQUS model fitting

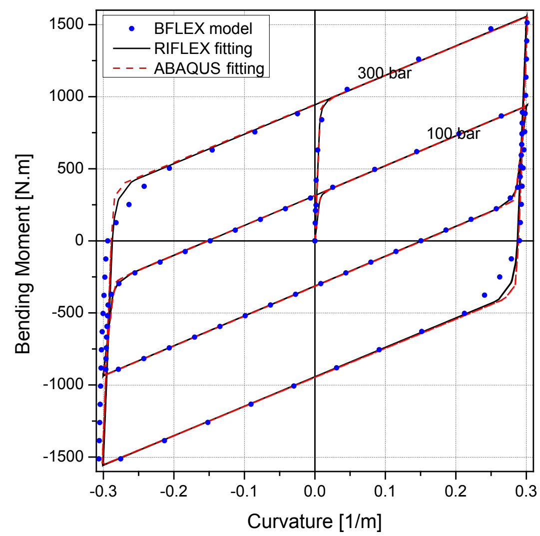

Figure A.2 – RIFLEX and ABAQUS fitting of BFLEX calculated bending moment x curvature for two internal pressures

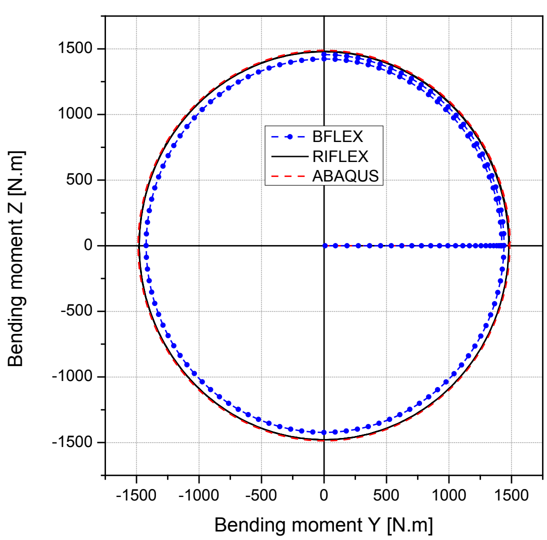

Figure A.3 – Bending moment for local Y x Z axis of 3D bending numerical experiment

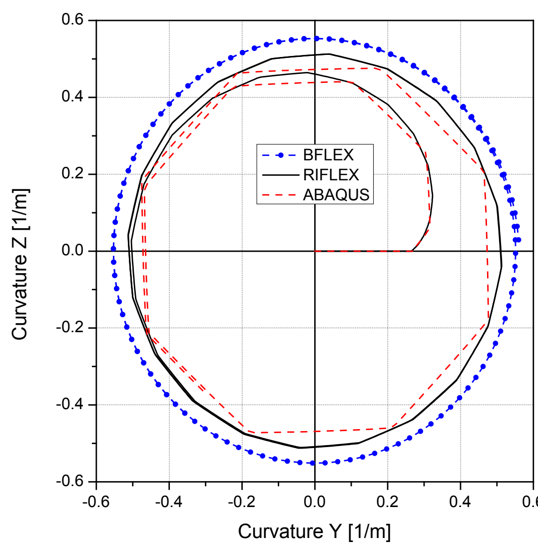

Figure A.4 – Curvature for local Y x Z axis of 3D bending numerical experiment

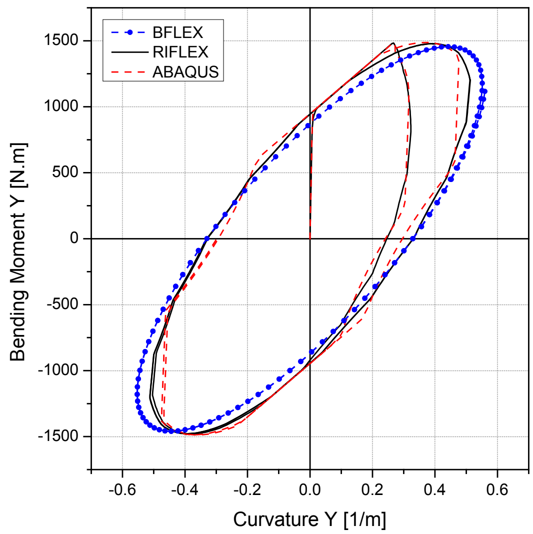

Figure A.5 – Bending moment x curvature for local Y axis of 3D bending numerical experiment

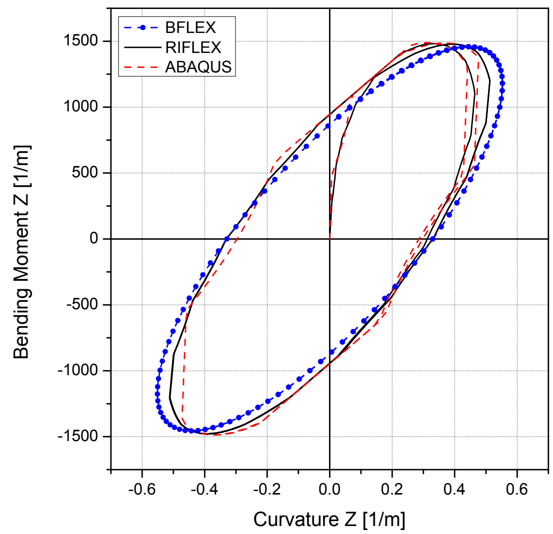

Figure A.6 – Bending moment x curvature for local Z axis of 3D bending numerical experiment

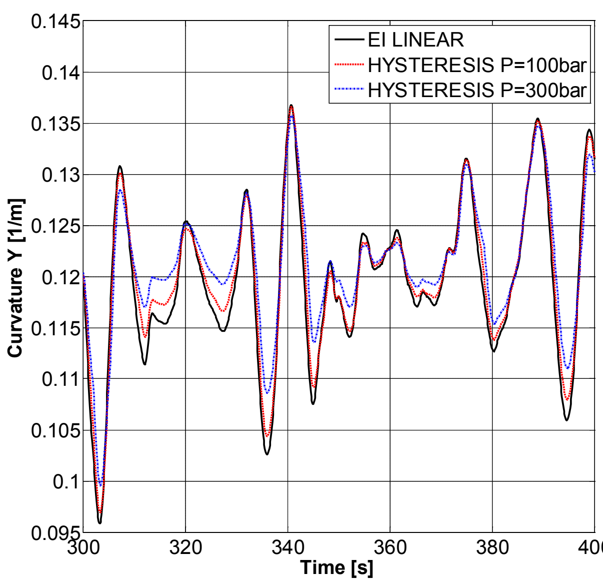

Figure A.7 – Local Y axis stochastic curvature time series for different bending models

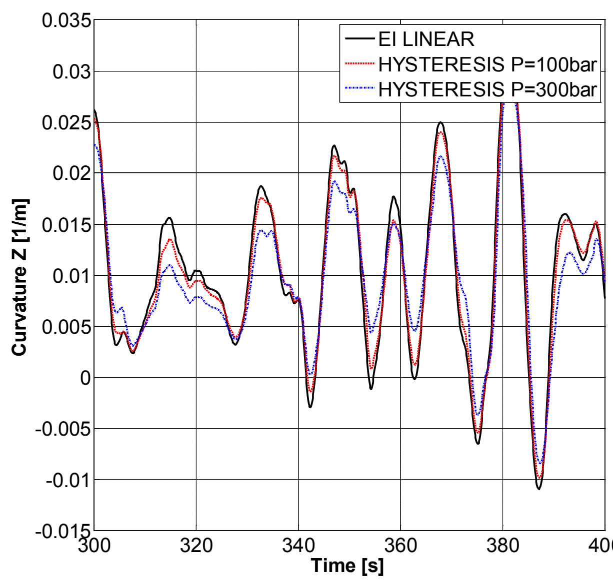

Figure A.8 - Local Z axis stochastic curvature time series for different bending models

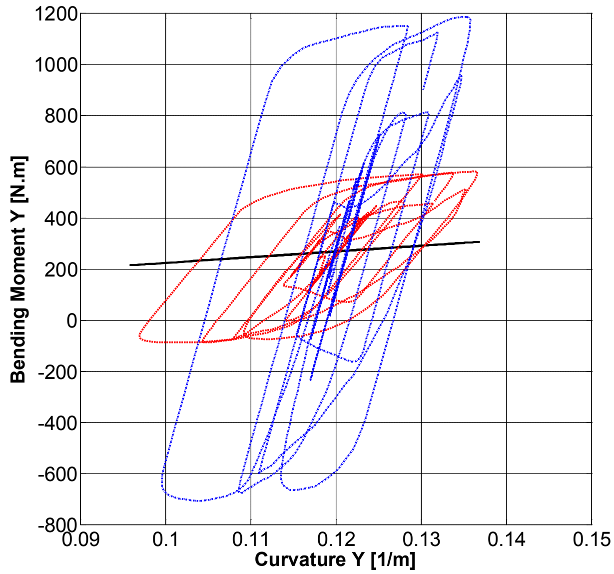

Figure A.9 – Bending moment x curvature for local Y axis (at top connection) of the fully coupled irregular wave case study

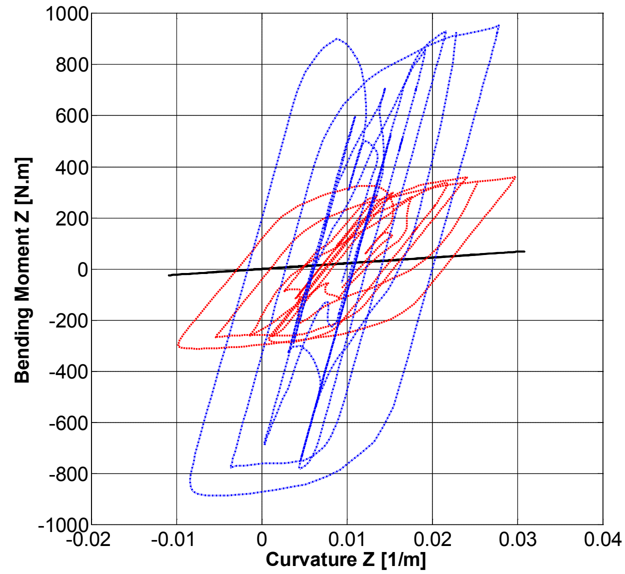

Figure A.10 – Bending moment x curvature for local Z axis (at top connection) of the fully coupled irregular wave case study