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MODELLING RISERS WITH PARTIAL STRAKE COVERAGE

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ABSTRACT

This paper compares model test data for risers with partial strake coverage to predictions made with the Vortex-Induced Vibration (VIV) prediction program SHEAR7 Versions 4.5 and 4.6. It is shown that new features in Version 4.6 substantially enhance the capability for predicting the VIV response of risers with partial coverage. Experimental data is taken from two large L/D tests: the NDP 38 m long riser tests and the Deepstar-Miami, 500 foot long riser. New methods are described for modeling risers partially covered with helical strakes. Key SHEAR7 parameters are recommended, based on parametric investigations to calibrate the model against the available experimental data. Recommended modeling procedures are described so as to facilitate implementation by SHEAR7 users in their VIV modeling tasks.

INTRODUCTION

The Deepstar “Factor of Safety” (FoS) project compared VIV prediction software with measurements from a 38m flexible cylinder tested at the MARINTEK basin for a consortium called the Norwegian Deepwater Project (NDP). The primary purpose of the FoS study was to determine the extent of conservativeness in the damage predictions from SHEAR7, VIVA and VIVANA when the recommended parameters are used. This was done in an attempt to determine the “inherent” factor of safety when using the above VIV prediction programs in engineering design. The test matrix included bare, partially straked and fully straked risers in sheared and uniform currents. [1]

Even though SHEAR7 V4.5 was predominantly conservative and only underestimated the damage rates at a few data points, the predictions for the partially straked riser in uniform current were particularly poor in the straked regions, over-predicting by a large amount. This is shown in *Figure 1* which plots the predicted and measured damage rates for 22 different current velocities. Each color represents a specific test (current velocity) and the data points within each color group

correspond to sensors mounted at different locations along the pipe.

In such plots of predicted vs. measured damage rates, when the points lie above the equality line ($\dot{D}_{predicted} = \dot{D}_{measured}$) the VIV prediction software is over-estimating the damage rates i.e. the program is being conservative. In general it is desirable that the predictions are conservative, but excessive conservativeness leads to unnecessarily expensive designs.

The excessively over-predicted cluster of points visible in *Figure 1* was the motivation for some improvements made to Version 4.6 of SHEAR7. V4.6 is an incremental update and can produce identical results to SHEAR7 V4.5 when the same parameters are used. However, a new feature makes it possible to define different reduced velocity bandwidths (dVr) in each structural zone of the model.

Figure 2 demonstrates the difference in the response prediction that this change allows. The figure compares the measured, SHEAR7 V4.5 and SHEAR7 V4.6 predicted strains along the length of the Miami riser when it was covered with strakes along its central section. The V4.6 predictions in the straked regions show a significant improvement over the V4.5 predictions.

The new method of modeling strakes relies on modeling straked zones in terms of their damping contributions rather than allowing them to belong to the power-in region. In order to improve the partial strake modeling capabilities of SHEAR7 the effect of a few key parameters had to be investigated. These included dVr , St , and the hydrodynamic damping coefficients.

These parameters were chosen by calibrating SHEAR7 with data from the 38m NDP riser which responded at modes numbers in the range of 5 to 15. Following this calibration, the same parameters were used to predict the response of the

Deepstar-Miami II pipe which responded at even higher mode numbers (up to mode 30). It will be shown that the parameters selected in the calibration with the NDP were well-suited to predict the response of the Miami riser. These same parameters will also work well in the prediction of risers with low mode number response ($n < 10$).

NDP AND MIAMI DATA

NDP riser

The NDP dataset was collected by MARINTEK for the Norwegian Deepwater Program. It involved towing a high length-to-diameter flexible 38m riser horizontally with and without suppression devices in uniform and sheared currents. The riser was heavily instrumented with both strain gauges and accelerometers. The maximum current velocity varied between 0.3 and 2.4 m/s. Two different types of strakes were tested with pitch to diameter and height to diameter ratios of [5 & 0.14] and [17.5 & 0.25]. Strake coverage was varied from 0% to 100%. Only the 50% coverage data with 17.5D/0.25D strakes were used in this calibration effort.

Table 1 summarizes the key parameters of the NDP riser. [2]

Table 1 NDP riser properties

Total Length	38.0 m
OD	27 mm
Wall thickness	3.0 mm
Bending Stiffness, EI	598.7 Nm ²
Young's Modulus	3.62E+10 N/m ²
Axial stiffness, EA	8.18E+6 N
Mass (in air), measured	0.761 kg/m
Mass ratio	1.62

Miami Riser

The Deepstar sponsored Miami II experiments, carried out by Prof. J.K. Vandiver and his research team, involved towing a 500ft long riser off the stern of a ship against currents in the Gulf Stream. During the riser's manufacturing process eight optical fibers with Bragg optical strain gauges every 7 ft were embedded in the pipe walls, resulting in a very densely instrumented riser. The strakes tested had a pitch of 17.5 D and a height of 0.25D [3,8]. Several different strake configurations were tested. These are shown in Figure 3

Table 2 summarizes the key physical properties of the MIT Miami riser.

Table 2 Miami riser properties

Length	152.4 m
ID	0.0249 m
OD	0.0363 m
Optical Fiber Diameter	0.0330 m
EI	613 Nm ²
Young's Modulus	9.21E+9 N/m ²
EA	3.32E+6 N
Weight in seawater	1.942 N/m
Weight in air w/ trapped water	7.46 N/m
Effective tension at bottom end	3223 N
Material	Glass fiber reinforced epoxy

The Miami current profiles varied from uniform to highly sheared. No attempt has been made to group the Miami-II test data into uniform or sheared groups. There were six runs with the bottom 40% of the model covered with strakes. There were three cases with 50% strake coverage at the center and three cases with 25% coverage at either end of the pipe.

DESCRIPTION OF SHEAR7 INPUT PARAMETERS

Reduced velocity (double) bandwidth

SHEAR7 calculates the reduced velocity along the length of the riser based on the current profile $U(x)$, the hydrodynamic diameter $D(x)$ and the natural frequency of the n^{th} mode f_n .

$$Vr_n(x) = \frac{U(x)}{D(x) f_n}$$

SHEAR7 centers a given mode's power-in region at the location where $Vr_n(x) = Vr_{crit}$.

$$Vr_{crit} = 1/St$$

The value of dVr then determines the spanwise extent of the power-in region; a broader reduced velocity range increases the size and correlation length for each mode's power-in region [4]

$$Vr_{max} = Vr_{crit}(1 + dVr/2) \quad Vr_{min} = Vr_{crit}(1 - dVr/2)$$

In SHEAR7 any wetted portion of the riser that is not part of the modal power-in region belongs to the power-out region and as such contributes to the hydrodynamic (modal) damping force.

Hydrodynamic damping coefficients

Hydrodynamic damping is calculated according to Venugopal's model [5]. This model takes into account the local response amplitude and the local reduced velocity.

$$\text{Modal damping ratio } \zeta_n = \zeta_{st} + \zeta_{n,h}$$

Where ζ_{st} is the modal structural damping and $\zeta_{n,h}$ is the modal hydrodynamic damping:

$$\zeta_{n,h} = \frac{R_{n,h}}{2\omega_n M_n}$$

Where $R_{n,h}$ and M_n are the modal damping coefficient and modal mass, respectively.

$$R_{n,h} = \int r_h(x) Y_n(x)^2 dx \quad \text{and} \quad M_n = \int m(x) Y_n(x)^2 dx$$

$$\text{For } Vr < Vr_{min}, \quad r_{sw}(x) = \frac{\omega \pi \rho D^2}{2} \left[\frac{2\sqrt{2}}{\sqrt{Re_\omega}} + k_{sw} \left(\frac{A}{D} \right)^2 \right]$$

$$r_h(x) = r_{sw} + C_{vl} \rho DV$$

$$\text{For } Vr > Vr_{max}, \quad r_h(x) = C_{vh} \rho V^2 / \omega$$

Where k_{sw} , C_{vl} and C_{vh} are the still water, low reduced velocity and high reduced velocity damping coefficients respectively.

St number

The NDP test matrix included testing the riser fully straked in various uniform currents. These results were used to estimate the Strouhal number for the straked regions. The PSD from each of these tests showed a broad uneven peak, which made estimating a Strouhal number difficult. The Strouhal number was determined from:

$$St = \frac{D f_{shedding}}{U}$$

and was found to vary between 0.08-0.10 for the AIMS 17.5D/0.25D strakes. The conservative approach calls for choosing the highest St number in the range of observed values.

LIMITATIONS IN VERSION 4.5

Figure 1 reveals that SHEAR7 V4.5 over-predicts some of the damage rates by as much as 3 orders of magnitude. To understand why this happens, it is instructional to look at a specific test and compare the measured and predicted damage rates along the riser. This is done for test 4980 (shown with black markers on Figure 1).

Figure 4 shows the SHEAR7 V4.5 predicted RMS displacement along the riser as well as the predicted and measured damage rates. It is clear that the SHEAR7 V4.5 predictions are extremely conservative in the straked portion of the riser. This behavior was observed in most of the NDP 50% straked, uniform flow cases leading to the cluster of over-predicted points, circled in black, in Figure 1.

A look at the SHEAR7 generated “.OUT files” for these uniform flow cases, reveals that the entire riser is power-in and the straked portion of the riser is assigned negative lift coefficients. Negative lift coefficient will reduce the total power into the riser and as a result the *Maximum Damage Rate* on the riser will be smaller than that for a bare cylinder (current method of modeling partial strake coverage). However, modeling strakes this way fails to capture the observed behavior of partially straked risers in uniform currents; which typically have power-in zones (and maximum Disp.) within the bare portion of the riser and an exponentially decaying response in the straked portions of the riser. V4.5 predictions do not capture well the decaying response in straked regions.

IMPROVEMENTS TO VERSION 4.6

SHEAR7 V4.6 allows the user to define a different *Reduced Velocity Bandwidth* (dVr) for each structural zone on the riser. Assigning straked zones smaller St and dVr prevents a given mode's *power-in* region; centered on a bare portion of the riser, from extending into the straked region. This then causes the straked portion to be *power-out*. This happens because the 'jump' in St values between the two structural zones (straked and bare) will change the localized $\frac{f_{shedding}}{f_n}$ ratio considerably, forcing the *power-in* length to stop at the interface of the two zones.

It is important to note that the inverse also applies, i.e. There will be modes that have *power-in* lengths covering only the straked portions of the riser with the bare zones being *power-out* (this is especially true in sheared currents). This is not a problem however because if the Straked Structural Zone uses the appropriate C_L curve -one with very little positive lift- the total power into this mode will be very small and this mode will be dropped (cut-off), when compared to more powerful modes.

Figure 5 demonstrates the significant difference in response prediction made possible by these changes in V4.6. The figure

shows how the predicted RMS displacement and damage rate vary along the length of the riser. Note the exponentially decaying displacement in the straked portion of the riser.

With the straked regions modeled as power-out, calibrating V4.6 involves changing the three hydrodynamic damping factors (in the straked structural zone) until the predicted damage rates approach the measured data but are still conservative. Figures 6a, b, c demonstrate the effect of changing the hydrodynamic damping coefficients for the NDP riser. Specifically Figure 6a shows the difference in predicted damage rates for $k_{sw}=0.2$ to 0.6. Similarly, the predicted damage rates for $C_{vi}=0.18$ to 0.9 are shown in Figure 6b.

Note that in Figure 6c the predicted damage rates for $C_{vh}=0.2$ to 0.8 produce identical results. This is because the current profile is uniform and since the St value for the straked zone is smaller than that in the bare zone, the strakes are always in the 'low reduced velocity' region and the C_{vh} damping coefficient is irrelevant to the hydrodynamic damping calculations. This meant that the appropriate value of C_{vh} had to be determined primarily from the sheared flow tests.

This process was repeated for all the NDP uniform and sheared flow 50% strake coverage tests until a satisfactory set of damping coefficients was established. These were found to be $k_{sw}=0.4$, $C_{vi}=0.5$, $C_{vh}=0.2$. The recommended modeling parameters are summarized in Table 3.

The interested reader is referred to the Appendix, where hydrodynamic damping coefficients are calculated from data from free and forced vibration tests on strakes of a similar strake design. The damping coefficients calculated are similar to those obtained through the calibration procedure.

Table 3 Recommended parameters for partially straked risers SHEAR7 V4.6

Recommended Parameters for Partially Straked Risers for SHEAR7v4.6	
Parameter	Value
Bare regions	
Ca	1
St	0.18
Cl table	1
Damping coefficients	0.2, 0.18, 0.2
Vr bandwidth	0.4
Straked regions	
Ca	2
St	0.10
Cl table	5
Damping coefficients	0.4, 0.5, 0.2
Vr bandwidth	0.25
General	
Cl reduction factor	1
Primary zone amplitude limit	0.3
Power Cutoff	0.05

Figures 7 & 8 show the results of modeling the NDP 50% straked riser using this approach. Figure 7 compares the SHEAR7 V4.6 predictions to the total cross flow measured Damage for the uniform flow cases. Note, how much closer to the *equality line* the black data points (test 4980) have moved when compared to Figure 1.

Figure 8 compares the SHEAR7 V4.6 predicted Damage Rate to the total cross flow measured Damage Rate for the sheared flow cases.

APPLICATION OF THE NEW STRAKE MODELING METHODOLOGY TO MIAMI II CONFIGURATIONS

The strake covered tests from the Miami II experiments can also be modeled using the parameters listed in *Table 3*. *Figures 9* through *11* compare the measured 1x strain against the SHEAR7 V4.6 predictions for a few representative cases from the Miami II dataset. The actual current profiles have been superimposed on each of these figures. *Figure 9* is an example of the Miami riser with strakes covering 25% of the pipe at each end. *Figure 10* shows the response of the riser when it had 50% strake coverage at its center and was exposed to a predominantly sheared current profile. *Figure 11* shows the response of the Miami riser with 40% strake coverage on its deeper end. The inclination of the pipe could be very large at the top ($x/L \approx 1$) as such SHEAR7 predictions near the top cannot be expected to match the measured data.

All three examples show a good agreement between measured and predicted strains with SHEAR7 usually erring on the conservative side.

Figure 12 shows the measured and predicted strains for 11 different tests from the Miami II experiments in various current profiles. Most points in *Figure 12* lie above the equality line (i.e. SHEAR7 V4.6 is being conservative) and agree within one order of magnitude with the experimental results. Specifically, 12% of the points have been under-predicted, 73% of the data points lie between the equality line and the $y=2x$ line and 15% of the predictions are more than twice as large as the measured values. A factor of 2 in strain corresponds to a factor of $2^3=8$ in damage rates, roughly one order of magnitude, entirely consistent with what is seen in *Figures 7 and 8*.

CONCLUSIONS

A new method for modeling partially strake covered risers with SHEAR7v4.6 is demonstrated. Key SHEAR7 parameters were determined by calibrating the program with the data available from the NDP 38m riser tests.

The calibration and the new methodology were validated by using SHEAR7v4.6 to successfully model the response of the MIAMI riser; which was very different from the 38m NDP riser, and had been tested in realistic current profiles. Version 4.6 is shown to have significantly improved partial strake modeling capabilities when compared to Version 4.5.

The new partial strake modeling methodology is shown to produce results in good agreement with the available experimental data. This modeling approach is intended for clean strakes with a pitch of $17.5D$ and a height of $0.25D$. Strakes with marine growth are considerably less effective at suppressing VIV and would have to be modeled with different lift coefficient tables, a topic of current research.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	Response Amplitude
\dot{D}	Damage Rate (1/yr)
n	Mode number
$D(x)$	Hydrodynamic Diameter
V_r	Reduced Velocity
dV_r	Reduced Velocity Bandwidth
St	Strouhal number
ζ_n	Modal damping ratio
ζ_{st}	Structural damping ratio
$\zeta_{n,h}$	Modal hydrodynamic damping ratio
f_n	Natural frequency of n^{th} mode (Hz)
ω_n	Natural frequency of n^{th} mode (rad/sec)
f^{shed}	Vortex shedding frequency
$m(x)$	Mass per unit length
M_n	Modal mass
$R_{n,h}$	Modal damping coefficient
$Y_n(x)$	Mode shape for n^{th} mode
k_{sw}	Still water damping coefficient
C_{vl}	Low V_r damping coefficient
C_{vh}	High V_r damping coefficient
Re_ω	Oscillation Reynold's number
$U(x)$	Current profile
C_L	Lift coefficient

APPENDIX

Estimating damping coefficients from C_L data

Prior to Version 4.6 strakes have been modeled using lift coefficient curves that are mostly negative. The disadvantage of this approach is that it is very hard to match the experimentally measured response in the straked regions.

Strakes can act like dampers and the response far into a straked region tends to decay exponentially from the bare zone values. In V4.6 strakes can be modeled in terms of their damping contributions.

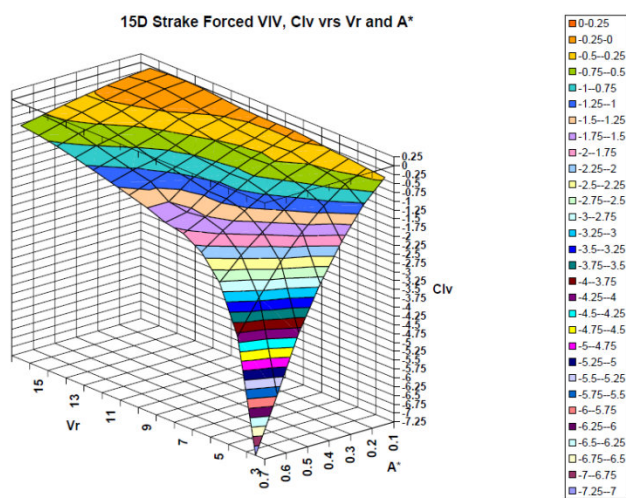
Vikestad [6] explains how the negative portion of a lift coefficient curve can be used to estimate the hydrodynamic damping coefficients in Venugopal's damping model. This involves expressing the lift coefficient in terms of the damping coefficients.

Two lift coefficients are defined; one in the low reduced velocity region and the other in the high reduced velocity region.

$$C_{L,lv} = \frac{-8\sqrt{2}\pi^3 (A/D)}{\sqrt{Re_\omega} Vr^2} - 4\pi^3 k_{sw} \frac{(A/D)^3}{Vr^2} - 4\pi C_{vl} \frac{(A/D)}{Vr}$$

$$C_{L,hv} = -2 \left(\frac{A}{D} \right) C_{vh}$$

The above expressions allow the calculation of the damping coefficients from C_L vs. A/D data at a specific reduced velocity. Schaudt et al [7] present the necessary data from extensive testing on various VIV suppression devices. Among these AIMS 15D/0.25D strakes were also tested in forced and free vibration tests in order to calculate lift and drag coefficients as a function of (A/D) and reduced velocity.



15-d strake lift coefficients.

Fig. A1 C_L as a function of V_r and A/D for the 15D AIMS strakes [7]

Because lift coefficient data for the 17.5D strakes wasn't available and since the 15D strakes from AIMS are very similar to 17.5D strakes, the data summarized in Figure A1 was used to estimate the damping coefficients.

The available lift coefficient data was separated into low and high reduced velocity groups. The C_L vs. A/D data in the low reduced velocity group was fitted with a polynomial of the form $y = \alpha x^3 + \beta x + \gamma$, whereas in the high reduced velocity region a linear fit through 0 was sought. The damping coefficients were then calculated from these curve coefficients.

Figures A2 & A3 show the available data and the calculated curve fits. The figures plot C_L vs A/D for several different reduced velocities.

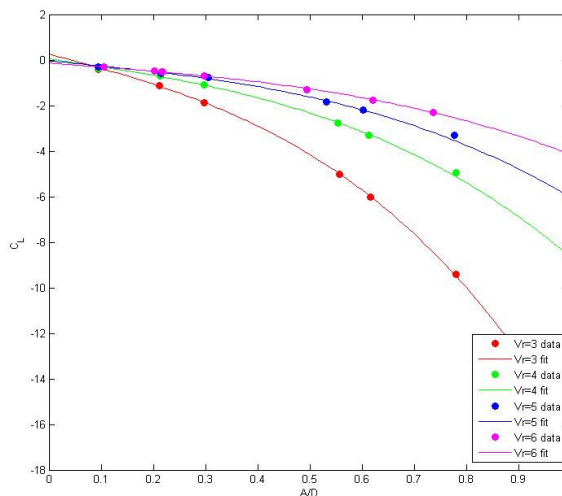


Fig. A2 C_L vs A/D at Low Reduced Velocities

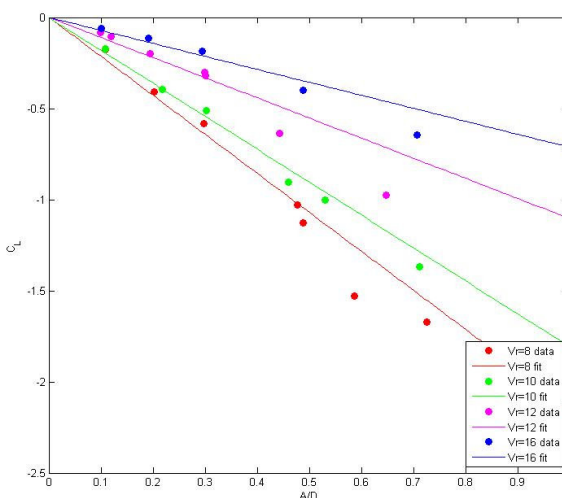


Fig. A3 C_L vs A/D at High Reduced Velocities

The calculated hydrodynamic damping coefficients are listed in Table A1. Highlighted in red is what is believed to be the lock-in region for these strakes; damping coefficients in this region are not applicable.

Table A1 Calculated Hydrodynamic Damping Coefficients

V_r	3	4	5	6	7	8	10	12	16
k_{sw}	0.74	0.68	0.76	0.67	0.51				
C_{vl}	1.49	1.09	.88	.82	0.5				
C_{vh}								0.55	0.36

Examining *Table A1* reveals that C_{vh} and C_{vl} vary with reduced velocity and are larger than those reported in the calibration process (*Table 3*).

SHEAR7 currently does not vary the hydrodynamic damping coefficients as a function of V_r . Therefore, the coefficients specified in the input file should be chosen with care, in order to ensure that SHEAR7 produces acceptable results over a range of V_r values.

If damping coefficients as large as those reported in *Table A1* had been used, SHEAR7 would have produced results much closer to the mean measured values with approximately the same number of points being over and under-predicted.

The damping coefficients in the calibration process were intentionally chosen to be smaller in order to ensure predominantly conservative results.

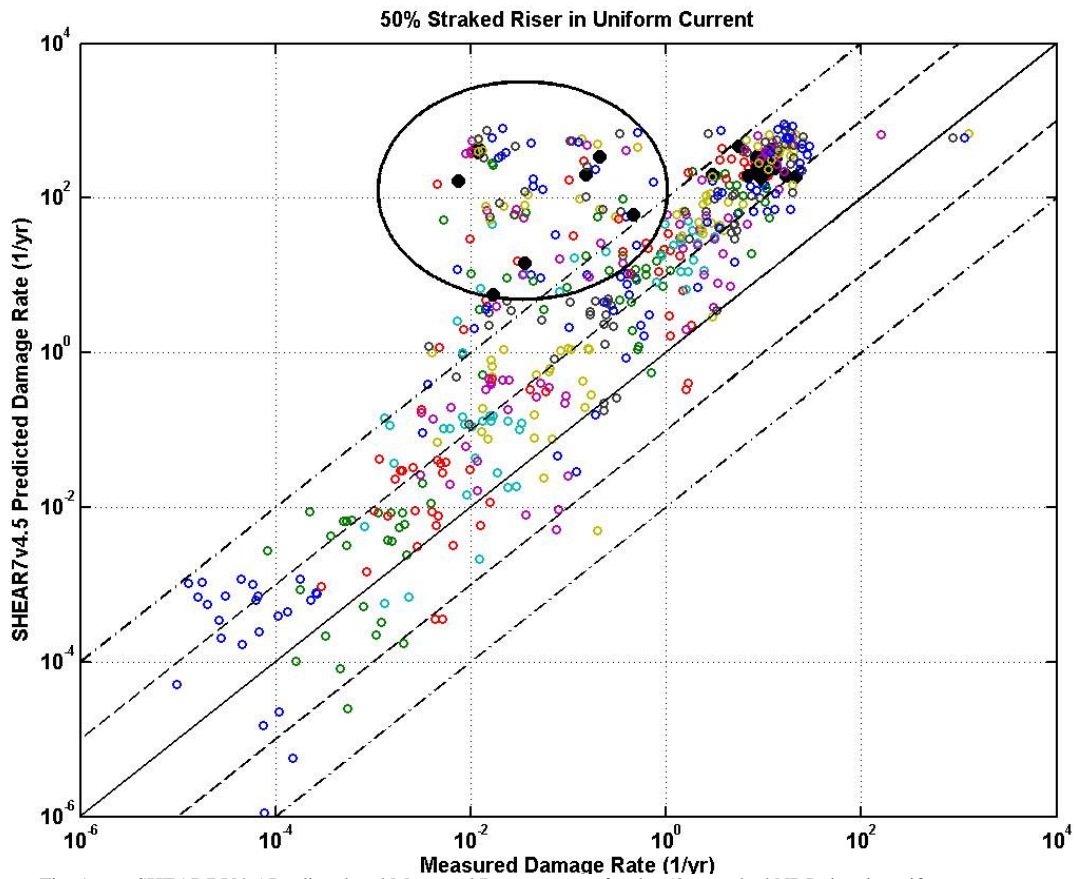


Fig. 1 SHEAR7 V4.5 Predicted and Measured Damage rates for the 50% straked NDP riser in uniform currents.

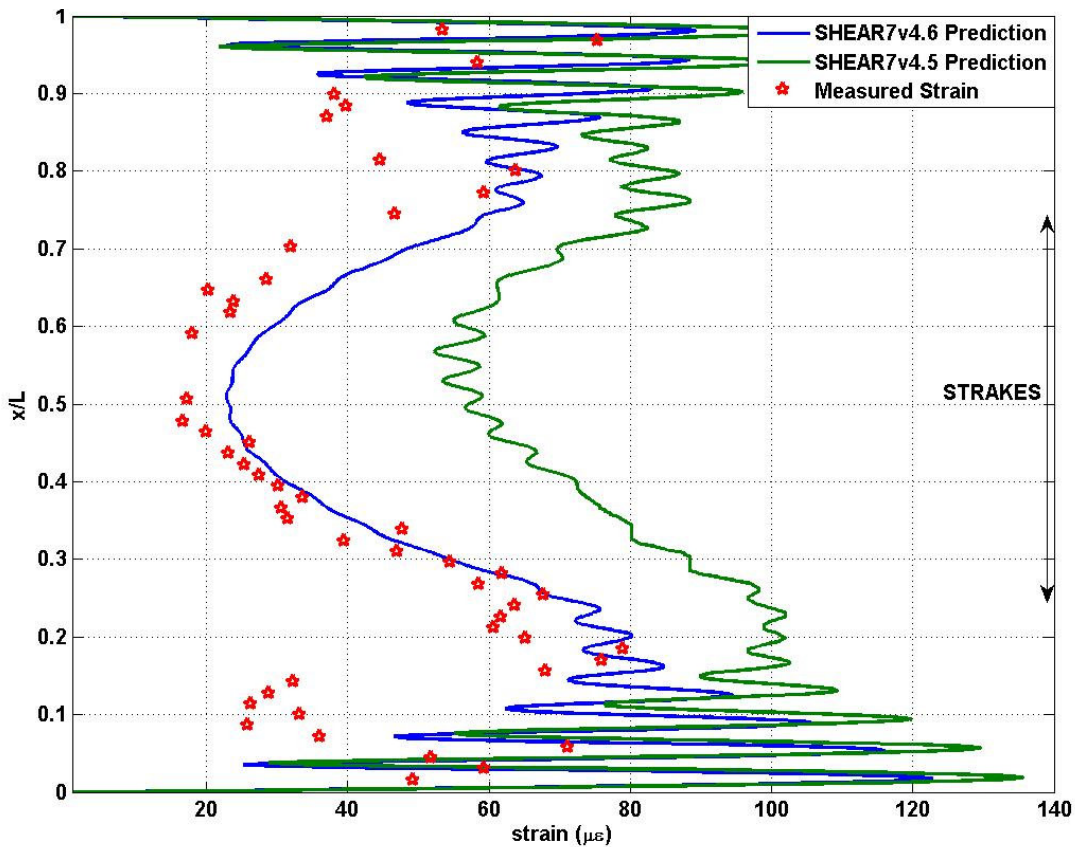


Fig. 2 Measured and predicted strain along the length of the Miami riser for test 20061023175030 using SHEAR7 V4.5 and SHEAR7 V4.6

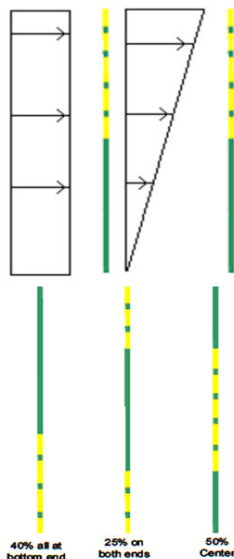


Fig. 3 Top - Strake configurations tested on the NDP riser
Bottom - Strake configurations tested on the Miami riser

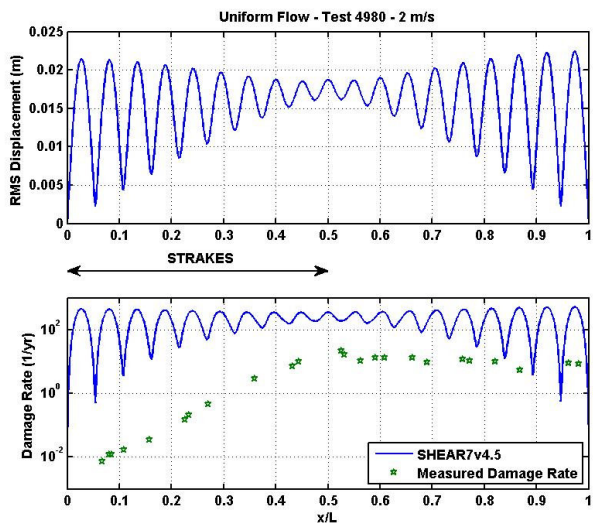


Fig. 4 Top - Version 4.5 predicted displacements (NDP Test 4980)
Bottom - Version 4.5 predicted damage rate compared to measurements

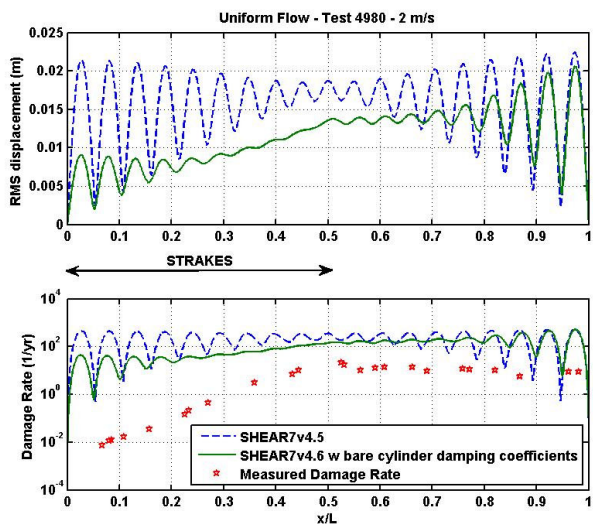


Fig. 5 Comparison of V4.5 to V4.6, RMS displacement (top), Damage Rate and Measured Damage Rate (bottom) using bare cylinder damping coef. for the V4.6 predictions. Note, the log-linear scale in the bottom plot.

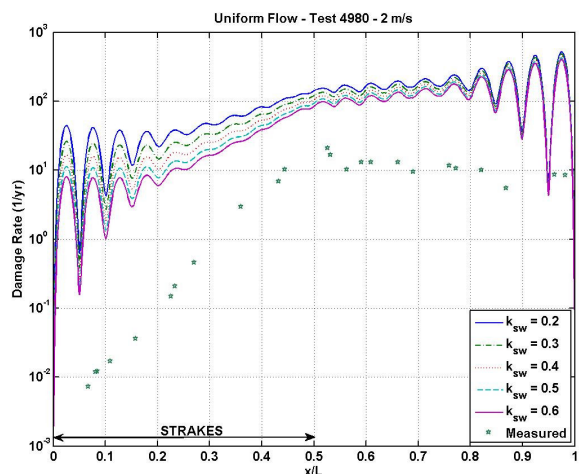


Fig. 6a Measured and Predicted(V4.6) damage rate along the riser for different values of k_{sw} in the straked structural zone.

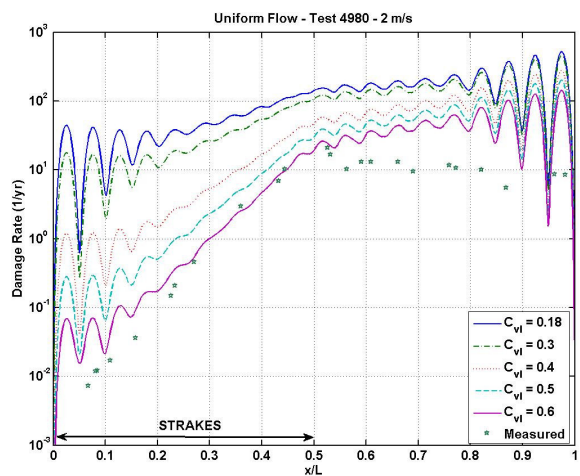


Fig. 6b Measured and Predicted(V4.6) damage rate along the riser for different values of C_{vl} in the straked structural zone.

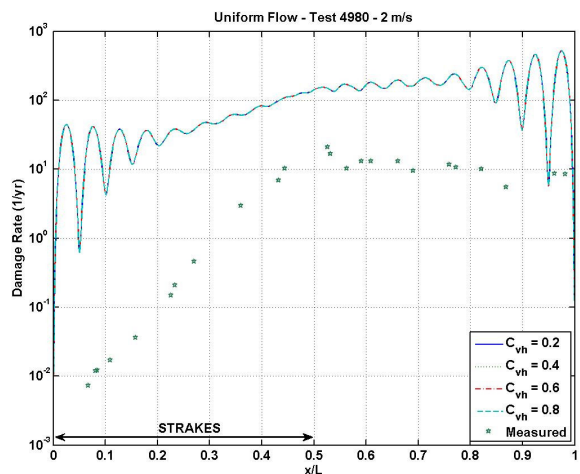


Fig. 6c Measured and Predicted(V4.6) Damage rate along the riser for different values of C_{vh} in the straked structural zone.

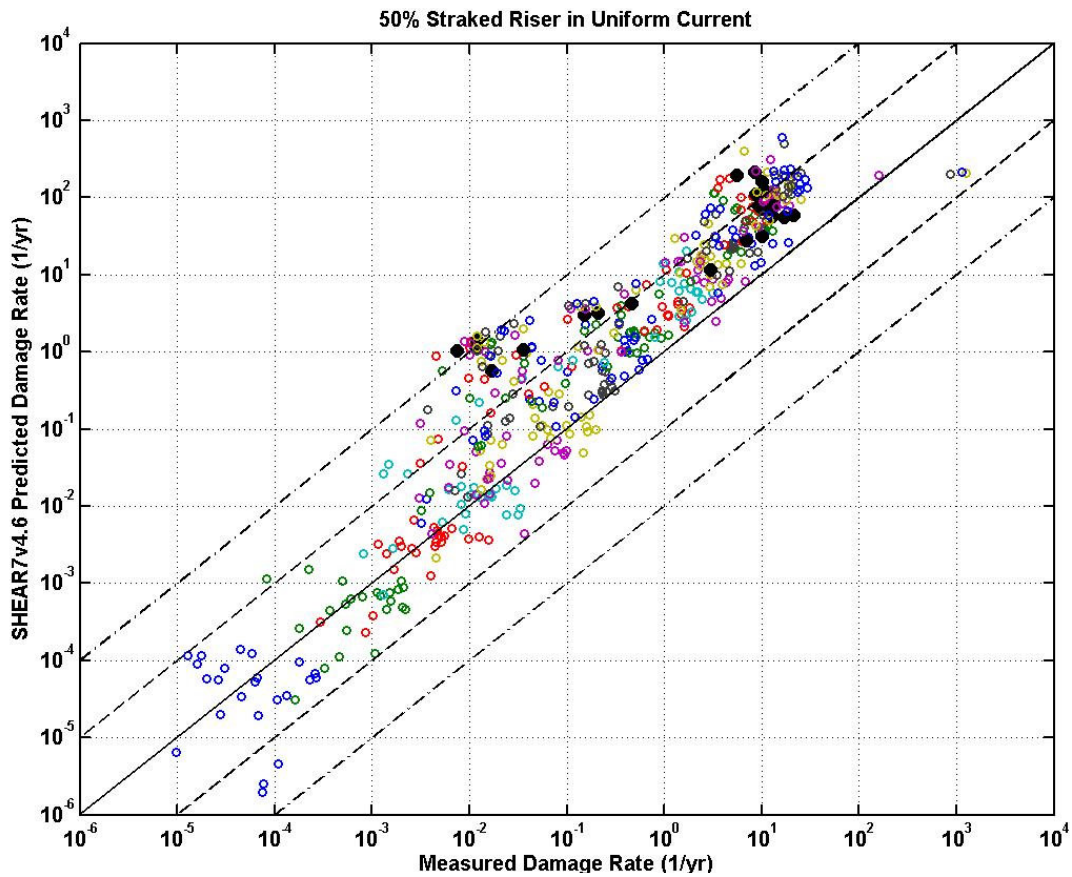


Fig. 7 SHEAR7 V4.6 Predicted and Measured Damage rates for the 50% straked NDP riser in uniform currents.

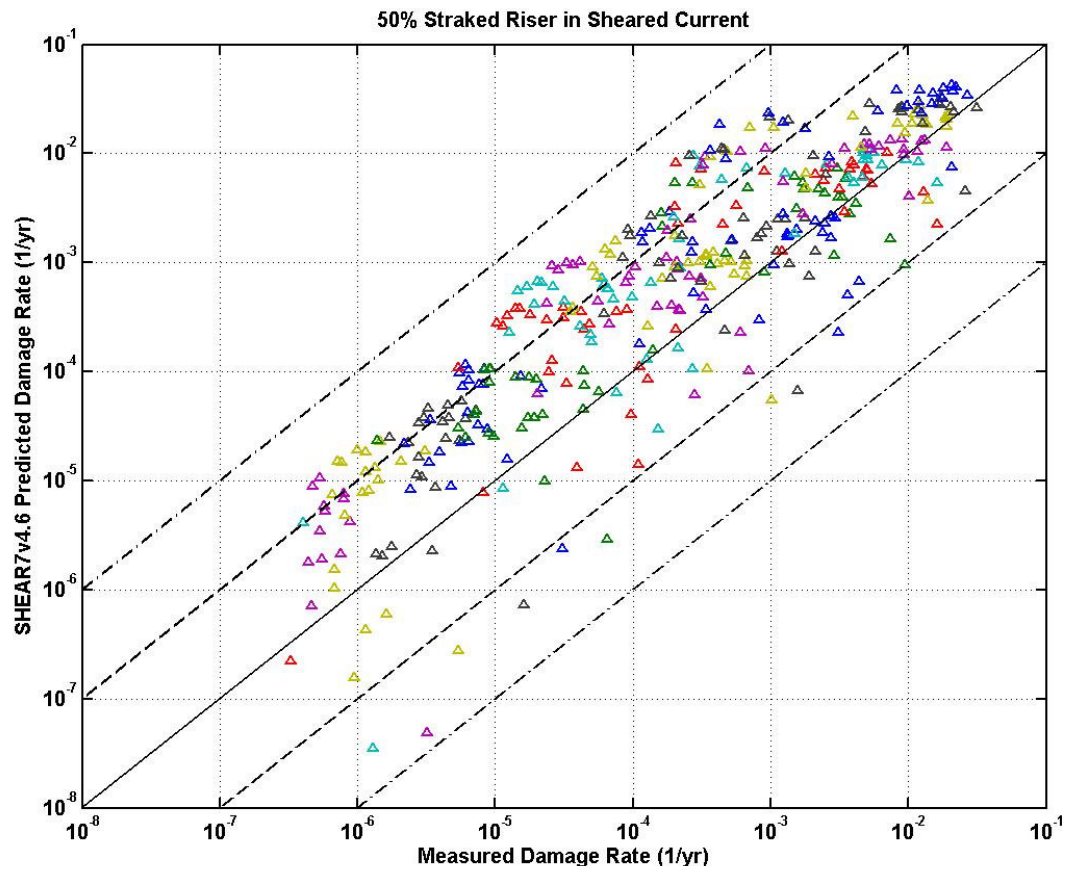


Fig. 8 SHEAR7 V4.6 Predicted and Measured Damage rates for the 50% straked NDP riser in sheared currents.

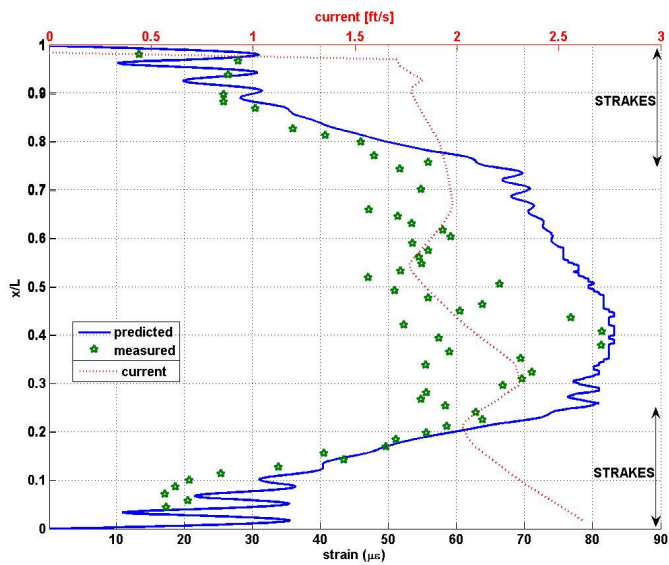


Fig. 9 Measured and Predicted strain ($\mu\epsilon$) along the Miami riser when it had strakes on both ends (200610211195122)

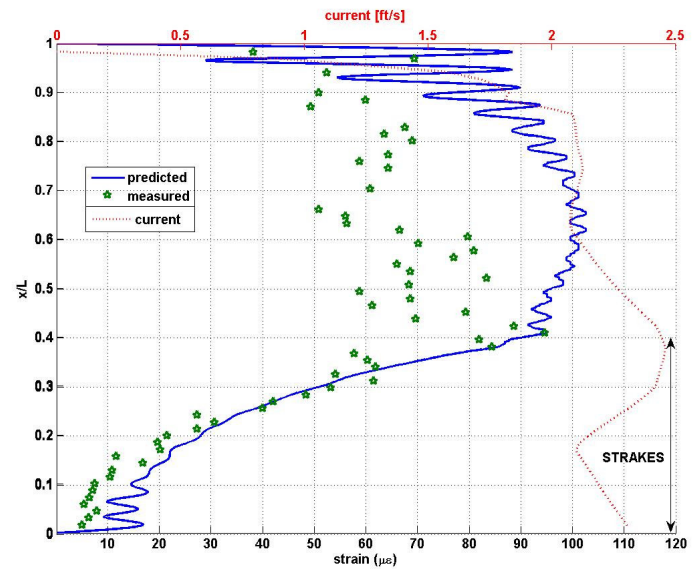


Fig. 11 Measured and Predicted strain ($\mu\epsilon$) along the Miami riser when it had strakes covering its deeper end (20061021214928)

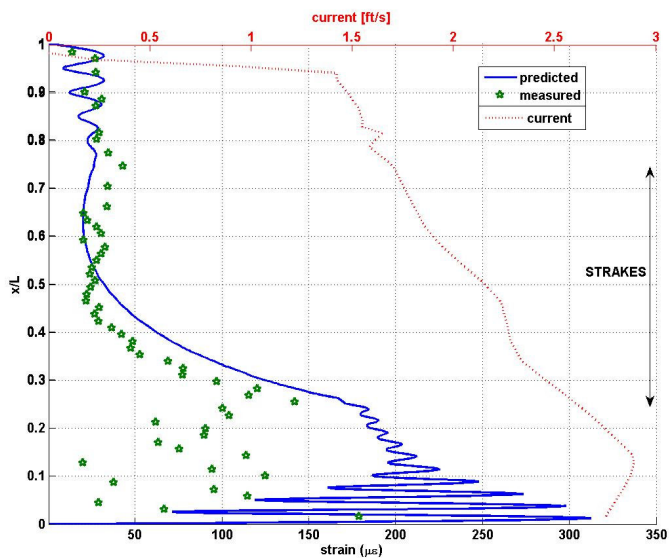


Fig. 10 Measured and Predicted strain ($\mu\epsilon$) along the Miami riser when it had strakes covering its central portion (20061023172650)

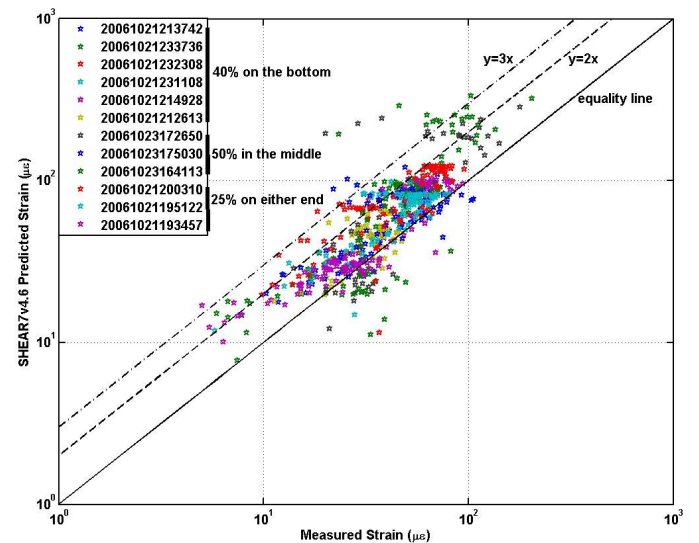


Fig. 12 SHEAR7 V4.6 Predicted and Measured Damage rates for the straked Miami cases.