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AN APPROACH TO INCLUDE OBSERVED VIV LIKELIHOOD IN DRILLING RISER FATIGUE ANALYSES

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ABSTRACT

Field measurements of the response of a number of drilling risers indicate that vortex-induced vibration (VIV) occurs significantly less often than predicted by the industry-standard fatigue analysis computer program SHEAR7 V4.4. Several comparisons to model tests and field data, including one published by BP and 2H in 2007 [1], demonstrate that this analysis program is generally quite conservative, given that VIV occurs. Furthermore, this conservatism does not take into account those situations in which VIV fatigue is predicted but none is observed in the field, which adds yet another layer of “hidden” conservatism to design analyses.

In an effort to address this and reduce conservatism to a more appropriate level, the probability of occurrence of vortex-induced vibration (VIV) is examined using full-scale measured data. The data has been collected over the past several years from five drilling risers without VIV suppression devices. These risers are on rigs under contract to BP at high-current-susceptible sites worldwide. Collectively, the data correspond to 9,600 10-minute field measurements, equivalent to 0.18 years of continuous monitoring. The riser response is obtained from motion loggers placed at selected positions along the riser as described in [1]. Each logger measures 3D accelerations and 2D angular rates. Through-depth currents are measured via Acoustic Doppler Current Profilers (ADCP).

By comparison of measurements to computer predictions based on the observed current profile, a relationship is developed between the intensity of the fatigue damage predicted and the probability that VIV is observed in the field. Subsequently, an approach is proposed for scaling analysis predictions to reflect the relative likelihood of VIV.

The database of measured and SHEAR7 maximum predicted fatigue damage rates is statistically characterized to determine how it may be used to determine factors of safety (FOS) for VIV design. A worked example for a deepwater drilling riser in the GoM is used to show how the FOS

methodology can be applied in the case of multiple design currents each with a different annual probability of occurrence.

INTRODUCTION

Field measurements of drilling riser response show that vortex-induced vibration (VIV) does not occur all the time that current speeds exceed those that would induce vortex shedding and excite the riser’s fundamental structural mode. However, SHEAR7 V4.4 (subsequently referred to as just SHEAR7) predicts the occurrence of VIV for the majority of the time that such a condition is fulfilled. The resulting VIV fatigue design is overly conservative. This conservatism is in excess of the conservatism that is generally inherent to SHEAR7 predictions when VIV does occur. To date, this on/off nature of VIV in the field has not been incorporated in predictions of VIV fatigue damage. The first objective of this paper is to introduce an approach to account for this non-occurrence of VIV in the field. It is important to point out that the SHEAR7 parameters have been calibrated in an effort to reduce the conservatism inherent to SHEAR7 predictions. The calibration yields an average over prediction factor of ten on fatigue damage when VIV occurs. While predicted VIV amplitudes would be different using the software recommended parameters, the on/off relationship between predicted and measured VIV would not be affected by this calibration approach.

A second objective is to show that the data in a database of measured and SHEAR7 predicted damage rates is well-represented by a continuous statistical distribution. From this distribution, the probability of a single SHEAR7 fatigue damage value exceeding the measured fatigue damage is known. Using this probability value, it is possible to determine the required factor of safety for drilling riser VIV analysis in a single current condition given an assumed confidence interval.

Subsequently, a worked example is given for a representative deepwater drilling riser in the GoM using Monte

Carlo simulations to determine the required FOS for VIV fatigue damage.

NOMENCLATURE

- CDF – Cumulative Distribution Function
- DNV – Det Norske Veritas
- FDR – Fatigue Damage Rate
- FOS – Factor of Safety
- GoM – Gulf of Mexico
- PDF – Probability Density Function
- PoO – VIV Probability of Occurrence
- VIV – Vortex Induced Vibration

LOCAL VS GLOBAL BIAS AND SCATTER

In previous studies [1], SHEAR7 predictions and measured fatigue damage comparisons were based on the maximum fatigue damage along the length of a drilling riser for each VIV event recorded in the field, irrespective of whether the maximum damage in the prediction occurred at the same location along the riser as in the measurement. This is a simplified approach used to reduce the quantity of data and simplify comparisons. In order to determine whether this simple approach is a valid alternative to location-specific comparisons, a detailed statistical assessment is conducted. Location-specific fatigue damage comparison statistics are calculated for each drilling riser and compared with the corresponding maximum fatigue damage statistics for that riser. The fatigue damage comparison statistics of relevance are the weighted fatigue damage bias α , the non-weighted fatigue damage bias β , and the scatter S_{X_d} . These are defined as follows:

$$\alpha = \frac{\sum FDR_{SHEAR7}}{\sum FDR_{measured}} \tag{1}$$

$$\beta = 10^{\mu_{X_d}} \tag{2}$$

$$S_{X_d} = \sqrt{\frac{\sum (X_d - \mu_{X_d})^2}{N}} \tag{3}$$

In Equations (2) and (3),

$$X_d = \log_{10}\left(\frac{FDR_{SHEAR7}}{FDR_{measured}}\right), \mu_{X_d} = \frac{\sum X_d}{N}$$

In the above equations, the summations are over the number of measured VIV events in the database. Note that the interpretations of Equations (1) and (2) are slightly different for fatigue damage comparisons based on the maximum fatigue damage along the length and those that are location-specific.

The weighted bias α is defined as such because it is driven by/weighted towards the high-damage events. On the other

hand, with the non-weighted bias β each event contributes an equal weighting towards the bias, irrespective of fatigue damage rate magnitude.

The results of the statistical assessment show that the location-specific scatter and fatigue damage bias only differ substantially from their global counterparts based on the maximum fatigue at the nodes of the theoretical mode shapes. At the anti-nodes of these theoretical mode shapes, which coincide with the locations of maximum fatigue damage rate, the differences between the scatter and bias values are at a minimum. Sample plots from the statistical assessment for one of the risers are presented in Figure 1 and Figure 2. Figure 1 shows the standard deviation of X_d (see Equation (3)) as a function of the normalized length x/L . On the other hand, Figure 2 shows the weighted bias α (see Equation (4)) as a function of the normalized length. In all drilling risers considered, the riser length analyzed extended from the just above the lower flex-joint ($x/L > 0$) to just below the upper flex-joint ($x/L < 1$).

Given the fact that large differences in the comparison statistics between the two approaches are only seen in locations of minimum fatigue damage (i.e., at the theoretical nodes), this “global” comparison of maximum fatigue damage along the riser is deemed representative and is the approach used herein.

The dataset consisting of all pairs (maximum measured fatigue damage rate, maximum SHEAR7 damage rate) for VIV events is subsequently referred to as the “max vs. max” database. This database has 1599 points and is shown graphically in Figure 3. Figure 3 shows that when VIV occurs in the field, SHEAR7 [2] over-estimates the fatigue damage by a factor of ≈ 10 on average, as discussed in previous work [1] and demonstrated again here in Figure 2. However, this is only representative of cases when VIV is actually measured in the field. Indeed, the results of the statistical assessment indicate that the fatigue damage bias increases (typically, by a factor of around two) when one additionally considers SHEAR7 fatigue damage from events where no VIV is measured. A method to account for these events is described in the next section.

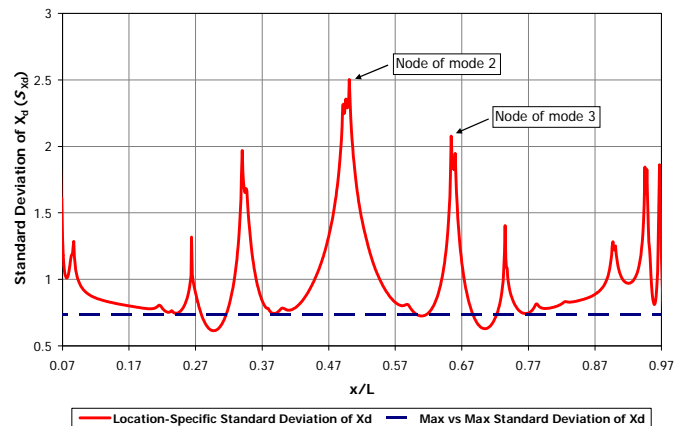


Figure 1 – Scatter Along the Riser Length for Measured VIV Events

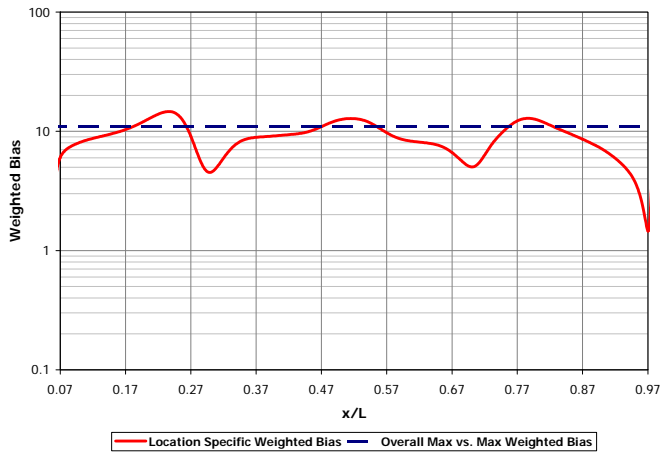


Figure 2 – Weighted Bias along the Riser Length for Measured VIV Events

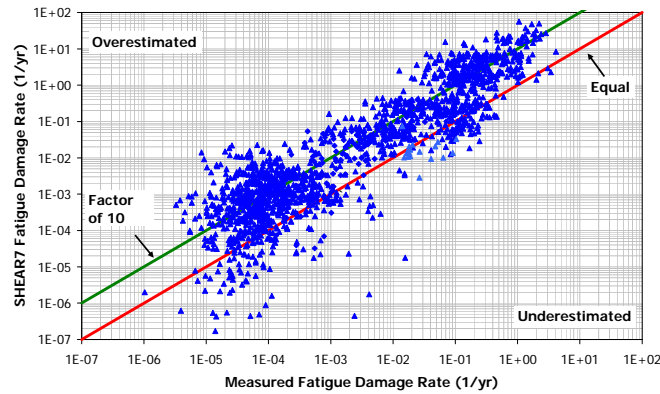


Figure 3 – Global Comparison: Max SHEAR7 vs. Max Measured Fatigue Damage Values in Database

PROBABILITY OF OCCURRENCE

As alluded to in the previous section, field measurements show that VIV does not occur all the time. To date, this non-occurrence of VIV in the field has not been incorporated in SHEAR7 VIV fatigue damage predictions.

In an effort to address this shortcoming, a relationship between the VIV probability of occurrence (PoO) based on the measurements and SHEAR7 predicted fatigue damage rate (FDR) is first established.

The measured fatigue damage rate data, including measurements of zero fatigue damage, in the max vs. max database is first sorted in ascending order by the corresponding SHEAR7 fatigue damage rate data. The sorted data is then parsed into a number (~50) of SHEAR7 bins corresponding to levels of SHEAR7 predicted FDR. In each bin, the ratio of measured samples for which VIV occurs to the total number of measured samples in the bin is calculated. This ratio represents the probability of VIV occurrence for that bin. The mean value

of SHEAR7 FDR in each bin is plotted against the probability of occurrence and a least-squares polynomial fit to the data points is obtained. The resulting data points and best-fit curve are shown in Figure 4.

The VIV probability of occurrence increases with an increase in the SHEAR7 predicted fatigue damage rates. That is, as the fatigue damage predicted by SHEAR7 increases, the more likely VIV is to occur in the field.

Using the best-fit curve, $PoO = f(\text{Mean SHEAR7 FDR})$, the value of PoO can be determined for a given SHEAR7 FDR value in the database, identified by the mean of the bin in which it falls in the database. The non-zero measured FDR value associated with this SHEAR7 FDR value is then multiplied by the PoO value, thus creating a “likelihood-factored” value that accounts for zeros that are not predicted by the software. This is repeated for all SHEAR7 FDR values in the database. As shown in Figure 5, comparisons of predictions to the likelihood-factored measured data is shifted are even more conservative than those for unfactored measured data, with the curves converging at higher measured damage rates where VIV occurrence is more likely. Note that the x-axis represents the mean value of the measured FDR in each SHEAR7 FDR bin.

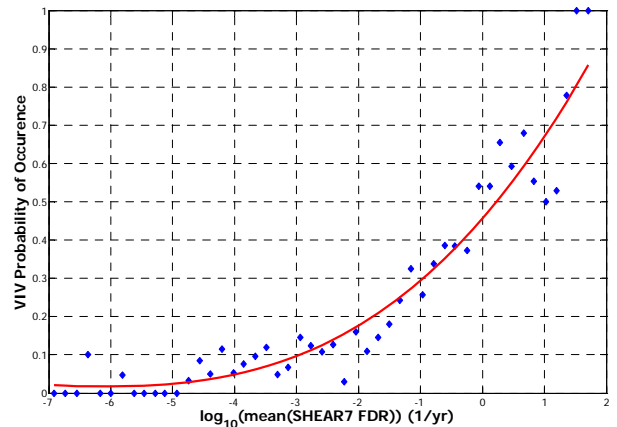


Figure 4 – Relationship between VIV Occurrence in the Field and SHEAR7 Fatigue Damage Rate

The measured FDR values need to be factored by the VIV probability of occurrence to account for the fact that a given value is unlikely to occur 100% of time. Indeed, without the correction, a given measured FDR value leads to an overestimation of the fatigue damage if it is assumed to apply 100% of the year.

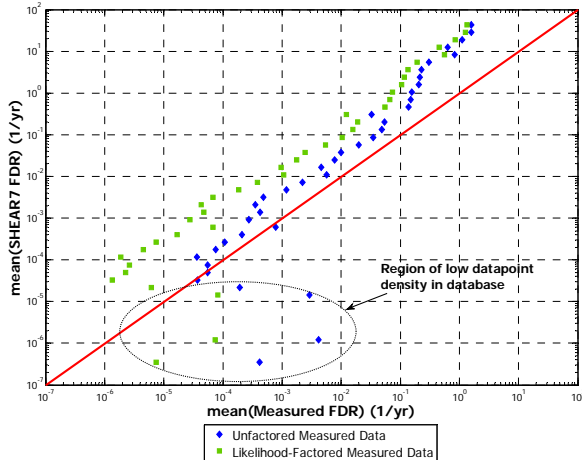


Figure 5 – Comparison of the Likelihood-Factored and Unfactored Measured FDR Data with the SHEAR7 FDR Data

STATISTICAL CHARACTERIZATION OF DATABASE

A critical component of this effort is the determination of factors of safety (FOS) that reflect uncertainty in VIV prediction and lead to consistency between SHEAR7 predicted data and measured data obtained from the monitoring campaigns. High scatter is evident in the comparisons of measured and SHEAR7 fatigue damage rates for any given current profile. This high degree of scatter implies the need for a high factor of safety. To calculate the FOS, the determination of the scatter in the aggregate riser fatigue damage is required.

Towards this end it is desirable to derive a continuous distribution that provides a reasonable representation of the FDR data in the database. However, it is first necessary to remove some of the data. Large differences between the measured FDR and SHEAR7 FDR seen at low fatigue damage rates ($< 7.31 \times 10^{-4}$ per year) are assumed to be due to low measured response which gives a low signal to noise ratio and introduces error in the measurements and subsequent data processing techniques. Moreover, such damage rates are insignificant from a practical standpoint. Hence, all FDR data below this threshold is removed before the distribution fitting process begins.

As shown in Figure 6, the normalized histogram of all the values of the natural logarithm of the ratio of the measured FDR and the SHEAR7 FDR is found to fit the probability density function (PDF) of a normal distribution (with mean μ and standard deviation σ derived from the data) reasonably well. Since the lognormal distribution is defined as the probability distribution of any random variable whose logarithm is normally distributed, it is natural to hypothesize that the data can be represented by a lognormal distribution. In order to test this hypothesis, the cumulative count of the values of the ratio of the measured FDR and the SHEAR7 FDR is compared to cumulative distribution function (CDF) of a lognormal distribution (with mean $E(X)$ and standard deviation

$StdDev(X)$ derived from the data). From Figure 7, the data is well-represented by a lognormal distribution.

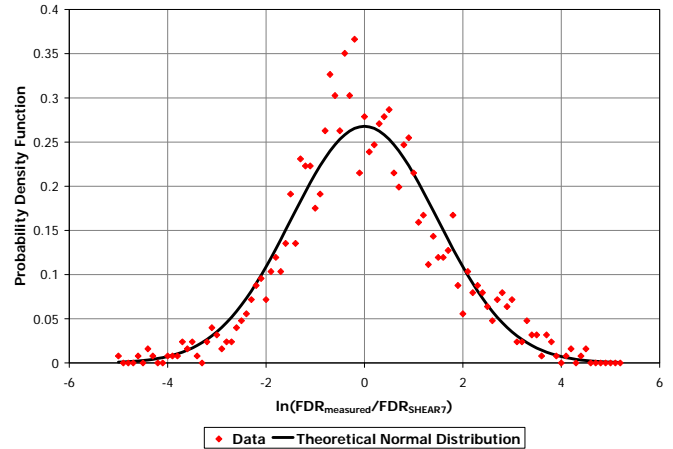


Figure 6 – Normalized Histogram vs. Theoretical Normal Probability Density Function, Mean Value Removed

Given the mean μ and standard deviation σ of the natural logarithm of $X = FDR_{measured} / FDR_{SHEAR7}$ (by definition, $\ln(X)$ is normally distributed), the mean value and standard deviation of lognormally distributed variable X are given by Equation (4) and Equation (5), respectively.

$$E(X) = e^{(\mu + \sigma^2/2)} \tag{4}$$

$$StdDev(X) = (e^{\sigma^2} - 1)^{1/2} E(X) \tag{5}$$

The mean over-prediction in SHEAR7 FDR predictions is calculated as $Bias = 1/E(X)$, where $E(X)$ is given by Equation (4). Subsequently, this is referred to as the bias. The value of $E(X)$ and the corresponding value of the bias are shown in Figure 7 for the theoretical lognormal distribution.

It is of interest to compare the variation of the lognormal fit $Bias$ with SHEAR7 damage intensity to those in the weighted bias (see Equation (1)), and the non-weighted bias (see Equation (2)). This is achieved by parsing sorted measured FDR data into a number of bins based on associated SHEAR7 predicted FDR and calculating each of these statistics for each bin. The results are shown in Figure 8 and indicate that the non-weighted bias always exceeds the weighted bias, which emphasizes the bias associated with the larger, more significant FDR values within each bin. Furthermore, the lognormal-fit $Bias$ provides a reasonable match to the weighted bias.

For comparison, a similar exercise is carried out for the likelihood-factored measured data. The results are shown in Figure 9. The results indicate that the non-weighted bias always exceeds the weighted bias and that the $Bias$ provides a reasonable match to the weighted bias. Note that for clarity, the

maximum value of the y-axis in Figure 9 is set to 100. There are values of the non-weighted bias that exceed this value.

From Figure 8, the bias varies as a function of SHEAR7 FDR from a maximum of approximately 15 to a minimum of approximately 0.35, whilst the *Bias* for all data is 3.11. However, as previously documented [1], and based on a visual inspection of Figure 3, a bias closer to 10 is expected. This discrepancy is due to the lognormal characteristics of the data which reduce the bias when based on accumulating fatigue damage. This may be illustrated by the following situation. Suppose we fix the FDR_{SHEAR7} value at 1, and consider the two points $FDR_{measured} = \{0.1, 10\}$. On a logarithmic scale, these points are equidistant from the equality line in Figure 3 and suggest an average bias of 1. However, it is clear if we compared aggregate measured to predicted damage that $(0.1 + 10)/(1+1) \neq 1$.

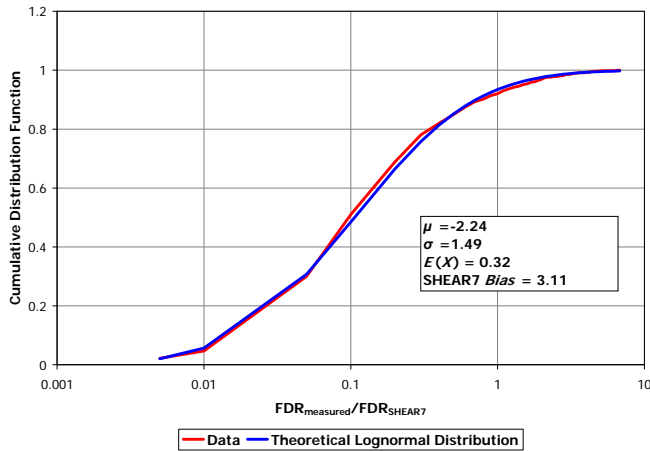


Figure 7 – Cumulative Count vs. Theoretical Lognormal Cumulative Distribution Function

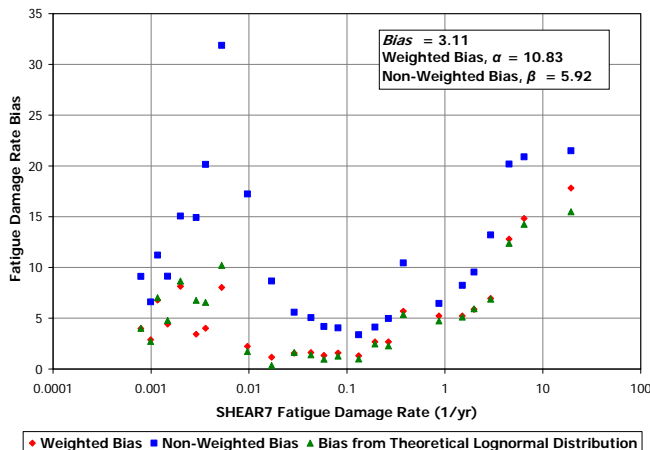


Figure 8 – Comparison of Weighted and Non-Weighted Biases with Bias Calculated from Theoretical Lognormal Distribution, Unfactored Measured Data

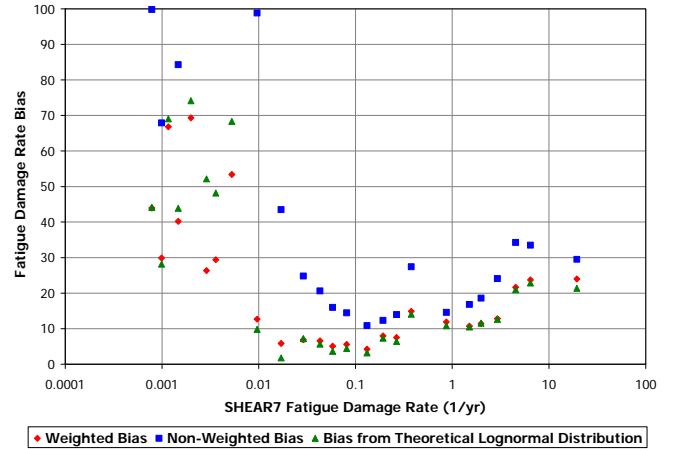


Figure 9 – Comparison of Weighted and Non-Weighted Biases with Bias Calculated from Theoretical Lognormal Distribution, Likelihood-Factored Measured Data

For this database, the lognormal distribution has been shown to provide a reasonable fit to the ratio of the measured FDR to the SHEAR7 FDR. Hence, the probability of a single SHEAR7 fatigue damage rate value exceeding the measured fatigue damage rate is known. This is equivalent to VIV analysis of a drilling riser with a single current. Based on an assumed probability of exceedence, p , the required factor of safety for VIV analysis with a single current can be determined as follows:

$$FOS = F^{-1}(1 - p | \mu, \sigma) \quad (6)$$

where $F(X)$ is the lognormal CDF.

Application of Equation (6) with $p = 1 \times 10^{-5}$, corresponding to a DNV high safety class [3], along with the values $\mu = -2.24$ and $\sigma = 1.49$ obtained from the distribution of $\ln(X)$, results in a required FOS of 61 for a single current, owing to the significant scatter in the ratio of measured to predicted data, which is illustrated in Figure 3. From a physical standpoint, it is expected that as the number of currents increases, the scatter in the aggregate prediction will decrease. This decrease would result in a corresponding decrease in the FOS required for a given probability of exceedence/failure p . The development of a modified version of Equation (6) that captures variation in scatter for multiple currents is ongoing. It is important to emphasize that from a design standpoint, it is those cases where SHEAR7 underestimates the fatigue damage rate calculated from the field measurements that are of concern. The FOS methodology presented here accounts for these cases.

Since a mathematical generalization is in development, the FOS methodology is illustrated for the case where multiple currents (events) and different probabilities of occurrence are involved via Monte Carlo numerical simulation. This is presented in the next section.

MONTE CARLO SIMULATION

A flowchart of the numerical simulations conducted is presented in Figure 10. The main steps can be summarized as follows:

1. The set of design currents and their associated probabilities of occurrence are used to obtain the SHEAR7 predicted total annual fatigue damage along the length of an example drilling riser;
2. The max vs. max database of fatigue damage rates is parsed into a number of SHEAR7 bins;
3. For each design current and each x/L value, the bin corresponding to the SHEAR7 predicted damage rate is identified;
4. A random sample from the set of measured fatigue damage rates in that bin is obtained;
5. Steps 3 and 4 are repeated for each design current and each x/L value, and the total annual measured fatigue damage calculated;
6. Steps 3, 4, and 5 are repeated N times;
7. Statistics of the simulated total annual measured fatigue damage are used in the calculation of the *FOS*.

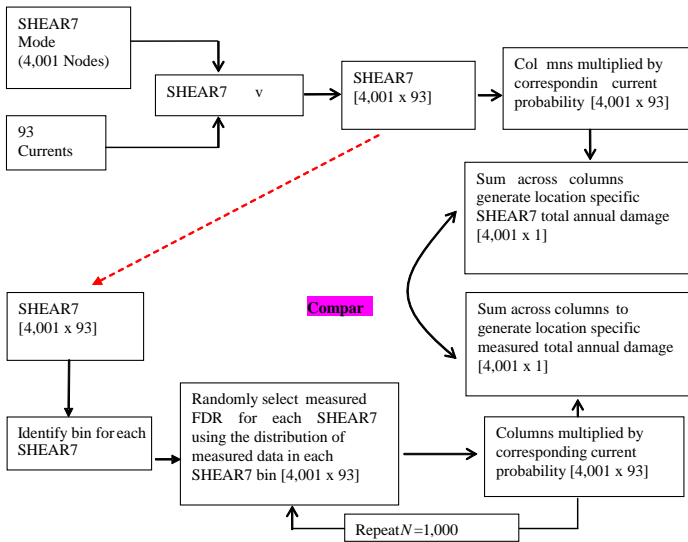


Figure 10 – Monte Carlo Simulation Methodology

The design currents (93 in total) for a representative drilling riser and site are used to generate sets of SHEAR7 fatigue damage rate values along the length of a drilling riser. The fatigue damage due to each design current is calculated at 4,001 uniformly spaced points along the length of the example riser. The fatigue damage values for each design current are then multiplied by that current's probability of occurrence. Finally, the total annual fatigue damage is determined by summing the factored damage due to each design current.

As described earlier, the SHEAR7 data (1,599 values) in the database is parsed into a set of $M = 50$ bins. A cut-off damage rate of 7.31×10^{-4} 1/yr is applied to remove

insignificant values of the SHEAR7 FDR from the Monte Carlo simulations. The number of SHEAR7 damage rate values in each bin is approximately the same.

The Monte Carlo simulation proceeds by first identifying for each calculated result its associated SHEAR7 FDR bin. A random sample from the distribution of measured data mapped to that SHEAR7 bin is then obtained and stored. This is repeated for each value in the SHEAR7 fatigue damage rate matrix. The result is a matrix of measured fatigue damage rates having size $4,001 \times 93$. Each column of this matrix is multiplied by the probability of occurrence of the corresponding design current. A sum across columns leads to the distribution of the total annual fatigue damage along the length of the riser (a $4,001 \times 1$ vector). This operation is repeated N times. The end result is a matrix of size $4,001 \times N$ representing N realizations of the total annual fatigue damage along the riser length.

Monte Carlo simulations are conducted for two sets of measured FDR data. In the first case, the measured data is not likelihood-factored. In the second case, the measured data is likelihood-factored using the polynomial fit between the measured VIV PoO and SHEAR7 predicted fatigue damage rate for the max vs. max data illustrated in Figure 4.

Figure 11 compares the total annual fatigue damage from the SHEAR7 prediction for the example riser (blue line) and the mean value of the simulated unfactored measured total annual fatigue (red symbols). The distribution of the *Bias* along the length can be determined by taking the ratio of the SHEAR7 fatigue damage and the mean value of the unfactored measured fatigue damage at each spatial point. Similar results for the case where the measured data is factored by the VIV probability of occurrence are presented in Figure 12. The *Bias* is significantly larger for the likelihood-factored measured data.

The mean value μ_m and standard deviation σ_m of the natural logarithm of the simulated total measured annual fatigue damage are then used to calculate the value $x_{m,p}$ required to meet the DNV High safety class (failure probability $P_f < 0.00001$). This is determined by calculating $x_{m,p} = F^{-1}(1-p = 0.99999 | \mu_m, \sigma_m)$, where $F(X)$ is the lognormal CDF. The distribution of $x_{m,p}$ along the length of the example riser for the unfactored and likelihood-factored simulated measured fatigue damage data are shown in Figure 11 and Figure 12, respectively.

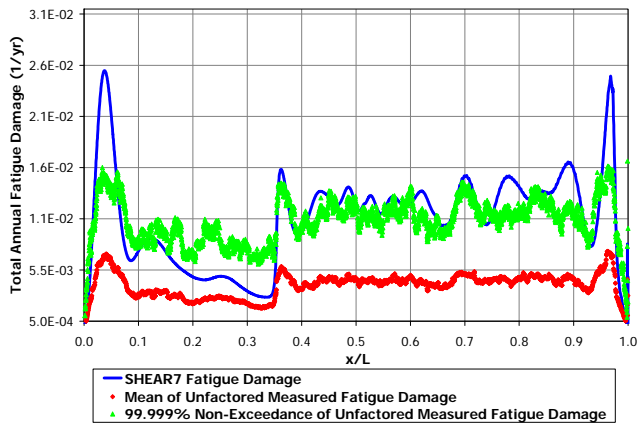


Figure 11 – Total Annual Fatigue Damage for SHEAR7 Data vs. Monte Carlo Simulated Unfactored Measured Data, DNV High Safety Class

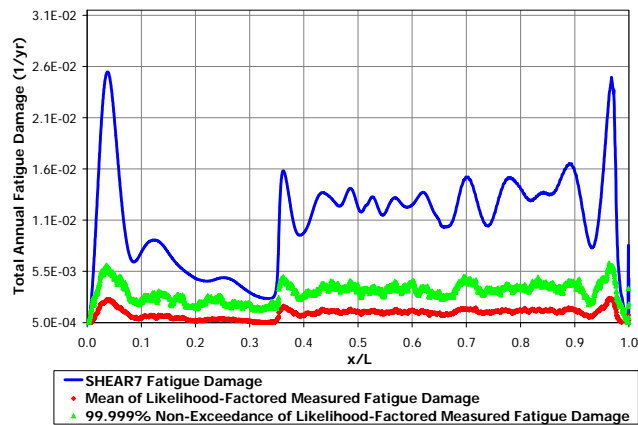


Figure 12 – Total Annual Fatigue Damage for SHEAR7 Data vs. Monte Carlo Simulated Likelihood-Factored Measured Data, DNV High Safety Class

Regions of Figure 11 where $x_{m,p}$ exceeds the SHEAR7 fatigue damage correspond to regions requiring a factor of safety greater than one. No such regions exist in Figure 12. In other words, taken at face value, the prediction already represents less than a 0.00001 chance of measured accumulated fatigue ever exceeding it.

The factor of safety at each spatial point is then given by the ratio of the SHEAR7 total annual fatigue damage and x_m . The results are shown in Figure 13. The FOS varies along the length depending on the bias and variation in total measured fatigue damage. The resulting FOS ranges from approximately 0.6 to 10 (the latter occurring off the chart near $x/L = 1$) for the unfactored measured data, and from approximately 0.2 to 2 for the likelihood-factored measured data. A factor of safety less than one indicates that the prediction already exceeds the high safety class considered herein.

The calculation of $x_{m,p}$, and therefore the local value of the factor of safety, is based on the assumption that the simulated

total measured annual fatigue damage at each spatial point is lognormally distributed. In order to examine the validity of this assumption, the normalized histograms of the natural logarithm of the total measured annual fatigue damage at a number of selected x/L values are examined. Figure 14, Figure 15, and Figure 16 show the histograms obtained for $x/L = \{0.04, 0.25, 0.50\}$, respectively. The first point, $x/L = 0.04$, is selected because it corresponds to the point of maximum bias (see Figure 11) and minimum FOS (see Figure 13). The other points are selected at random.

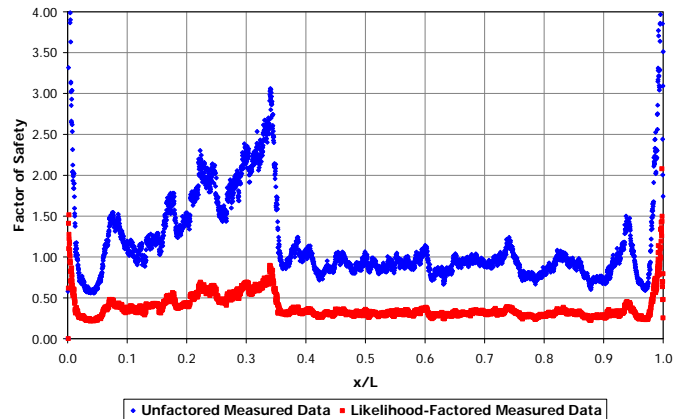


Figure 13 – Factor of Safety Derived from Monte Carlo Simulated Unfactored and Likelihood-Factored Measured Data

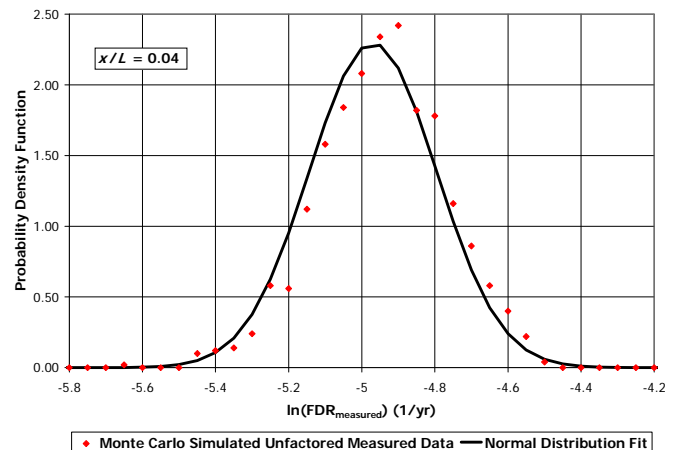


Figure 14 – Normalized Histogram of Monte Carlo Simulated Unfactored Measured Data at $x/L = 0.04$

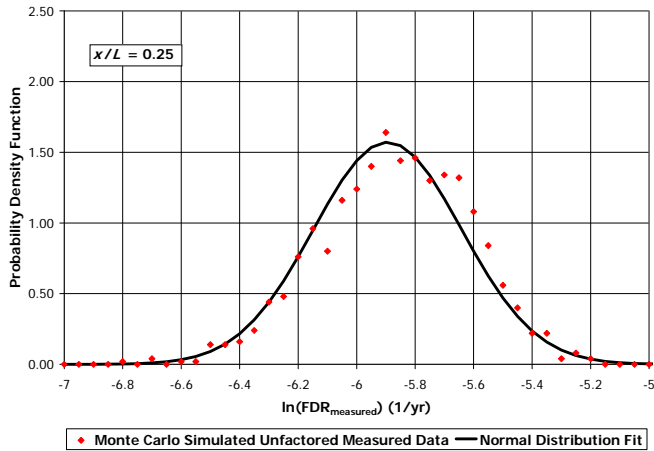


Figure 15 – Normalized Histogram of Monte Carlo Simulated Unfactored Measured Data at $x/L = 0.25$

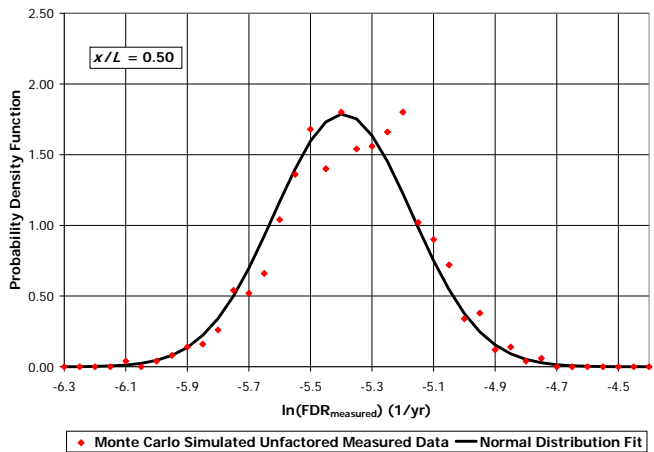


Figure 16 – Normalized Histogram of Monte Carlo Simulated Unfactored Measured Data at $x/L = 0.50$

The normalized histograms shown in Figure 14 - Figure 16 are in reasonable agreement with what would be expected from a normal distribution. The histograms are expected to converge to Gaussian with an increase in the number of iterations in the Monte Carlo simulations, validating the lognormal assumption mentioned above.

CONCLUDING REMARKS

SHEAR7 predictions and measured fatigue damage comparisons based on the maximum fatigue damage rate along the riser are an acceptable alternative to location specific comparisons. The maximum difference in the standard deviation (scatter) and in the weighted bias between the two approaches occurs at the nodes of the theoretical mode shapes, which coincide with the locations of minimum fatigue damage rates.

A relationship between the VIV probability of occurrence (PoO) based on the measurements and SHEAR7 predicted fatigue damage rate (FDR) is established. The VIV probability

of occurrence increases with increasing SHEAR7 fatigue damage rate. The effect of incorporating the VIV likelihood is to shift comparisons with predictions towards even greater conservatism compared with predictions against unfactored measured data.

The ratios of fatigue damage rate data in the max vs. max database are shown to be well represented by a lognormal probability distribution. The standard deviation and mean of the distribution are used to derive a factor of safety (FOS) required to satisfy the DNV High Safety Class for an individual current condition. When the data is parsed into a number bins according to SHEAR7 damage intensity, the variation of the bias derived from statistical properties of the lognormal distribution is found to be in reasonable agreement with the weighted bias.

In order to illustrate the “aggregate” FOS in a realistic scenario, when multiple currents (events) and different probabilities of occurrence are involved, the design currents for a deep water site in the Gulf of Mexico are first used to generate total annual SHEAR7 fatigue damage along the length of a nearby drilling riser. A Monte Carlo simulation is then used to generate a set of realizations of the total annual measured fatigue damage. Simulations are conducted for both unfactored and likelihood-factored measured data. When likelihood-factored measured data are considered, the required FOS to meet the DNV High Safety class is always less than for the unfactored data. Furthermore, it is often less than one, indicating conservatism in excess of high safety class inherent to the prediction. Note that this result is particular to the worked example herein and is not purported to be universal but, perhaps, indicative of similar scenarios.

In general, the findings described in this paper are limited to a large, but by no means exhaustive, database gathered for a particular class of risers; namely, drilling risers in deep water without suppression devices.

It is anticipated that the findings presented herein are repeatable in SHEAR7 V4.5. Indeed, a recent study finds little difference in FDR predictions between V4.4 and V4.5 for the predominately single-mode response characteristic of the deepwater drilling risers used in the database [4]. Comparisons against other available VIV fatigue analysis programs have not yet been made.

Future work is based on deriving mathematical relations that will permit a designer to calculate a modified FOS that accounts for the number of currents (events) analyzed with SHEAR7, as well as their annual probabilities of occurrence. This would presumably supplant the necessity for the Monte Carlo simulation approach taken to the worked example in this paper.

Additional future work would focus on gaining a better understanding of those situations in which VIV does not occur in field measurements despite the presence of currents that could potentially excite VIV. It is desirable to develop a set of parameters, such as current intensity, shear or measure of

variability in through-depth directionality, that determine the occurrence or non-occurrence of VIV in the field.

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