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A novel approach to expand the reach of classic structural health monitoring systems

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SOMMAIRE

Le monitoring de la structure des navires est aujourd’hui un sujet de recherche récurent, presque « à la mode ». En plus des inspections périodiques qui permettent de détecter des avaries et de suivre l’avancement de la corrosion, il peut en effet se révéler intéressant de suivre d’une manière plus continue la réponse structurelle, par exemple pour s’assurer que le navire opère bien dans les limites déterminées lors de la conception.

Depuis quelques années, Bureau Veritas travaille sur une méthode innovante, basée à la fois sur des mesures directes et des calculs numériques, qui vise à augmenter la portée des systèmes actuels de mesure de contrainte sur les navires. En plus du suivi des zones instrumentées, elle permet d’étendre le suivi dans le temps des contraintes sur des détails structuraux non-instrumentés. Ce mémoire vise à expliquer cette méthode « hybride » en la situant par rapport aux autres méthodes de monitoring, et présente deux cas d’application sur un navire militaire et un FPSO.

SUMMARY

Structural health monitoring of ships has become a recurring subject of research, almost “trendy”. On top of periodic inspections, which allow the detection of structural damage and the monitoring of corrosion, it could indeed prove useful to continuously monitor the structural response of the ship, for instance to make sure that it operates within the bounds determined during the design phase.

In the past few years, Bureau Veritas has been working on a novel method, based both on direct measurements and numerical computations, which aims at increasing the reach of classical structural health monitoring. On top of the monitoring of instrumented areas, it allows the monitoring of non-instrumented structural details. This paper aims at explaining this “hybrid” method by placing it in the context of other monitoring approaches, and presents two actual application cases on a navy vessel and an FPSO.

1. INTRODUCTION

The world we live in is now a digital word; structural monitoring of ships and offshore units is therefore more than ever at the heart of our concerns. Sensors are everywhere, and digital tools are now able to deal with this amount of data. The issue is no longer to measure, but to analyze and use this data. So why not monitor the structural health of your ship, your offshore wind turbine, your FPSO?

Whatever the ship or the offshore unit, operating conditions taken into account in the design phase are only hypotheses. For example, for those container ship structural details that are verified with a spectral fatigue analysis, Bureau Veritas (see [1]) requires the sea states to be represented by an average scatter diagram and by equiprobable wave directions, and the operating conditions to be simplified by a single loading condition and forward speed. As soon as the ship is actually sailing, those hypotheses become obsolete and you actually don't really know what is happening for all those structural details that were so finely designed. From then on, the only solution is to regularly inspect the ship to verify its structural integrity.

A monitoring system can have many advantages: to ensure that the operating limits defined in the design phase are not exceeded, to follow the fatigue damage accumulation on critical structural details, to provide support for inspections and maintenance, to extend the service life or simply to know more about what is actually happening to the structure (unexpected vibrations for example, as in the case of the flare tower of an FPSO presented in [6], or in the case of a container ship presented in [7]).

This paper takes over a method first developed for the measure of hull girder loads (see [2]). By taking advantage of stress sensors and of capabilities of hydro-structure simulations, it allows the computation of hot-spot stresses on non-instrumented structural details with sufficient accuracy. The advantages and drawbacks of this approach are detailed and compared with those of two other monitoring approaches more frequently used. Two validation cases are then presented, for a navy ship and for an FPSO.

2. CONCEPT

2.1. Classic structural monitoring using stress sensors

Classically, structural health monitoring is achieved by placing stress sensors at key locations on the structures, wherever the stresses have to be monitored. The amount of information is therefore always quite limited – you just cannot install sensors everywhere – and it is usually quite complicated to directly measure hot spot stresses due to high stress gradients at those locations. Only nominal stresses are therefore measured, and stress concentration factors are then used to get "useful" stresses for the assessment of fatigue damage in critical structural details.

Directly instrumenting the structure certainly gives a precise estimation of the stresses on the structure, but a limited one.

2.2. Virtual structural monitoring using hydro-structure digital simulations

With the development of hydro-structure simulation tools, a new type of monitoring is becoming more and more trendy, the so-called "virtual" monitoring. Its basic idea is to pre-compute transfer functions of stresses in critical structural details (as functions of wave headings and frequencies) and to combine them with wave spectra, either directly measured by wave radars or buoys, or computed by hindcast ocean models, as explained for example in [8] and [9].

Unlike classic monitoring, this approach can reach potentially all values of interest, anywhere on the structure. The downside is that it is fairly less accurate because the stresses computed in critical structural details are the end results of a whole chain of three numerical simulations: the wave spectra have to be computed first, then the hydrodynamic pressures, which finally have to be applied to a finite element model to compute the structural response.

2.3. Hybrid structural monitoring using the conversion matrix approach

To benefit as much as possible from the two approaches listed above, it is possible to use the conversion matrix method (see [2]), which is briefly recalled hereafter.

The basic idea is to find a linear relation between some input and output, denoted respectively X and Y hereafter. The matrix C defining this linear relation is called the conversion matrix:

$$Y = C \cdot X \tag{1}$$

To build this matrix, the input and output are expressed on a basis of distortion modes; with ξ being the vector of modal amplitudes for those modes, the input and output can be written as:

$$X = M \cdot \xi \tag{2}$$

$$Y = B \cdot \xi \tag{3}$$

The conversion matrix is then computed using the pseudo-inverse matrix defined by Moore-Penrose:

$$\widetilde{M}^{-1} = (M^T \cdot M)^{-1} \cdot M^T \tag{4}$$

$$C = B \cdot \widetilde{M}^{-1} \tag{5}$$

All that remains then is to choose the modal basis for this decomposition. Previous work (see [2]) showed that modes chosen among structural responses of the structure on regular waves (defined by their heading, frequency and phase) gave good result for the recomposition of hull girder loads. As it happens, this method can be used to reconstruct hot spot stresses too. This was shown for example in [7] to reconstruct the stresses at hatch corners of a container ship, based on the measurement of stresses at long base strain gauges (without local effect) further away in the structure.

This method can then be used to compute stresses everywhere in the structure, at least at all critical details, from the values measured at a limited number of sensors. The installation and maintenance cost can then be reduced, while keeping an acceptable precision because the input of the monitoring system is still directly measured on-board. Compared to the virtual monitoring approach, this approach gets rid of all the uncertainties related to the simulation of sea states by the hindcast model and to the computation of hydrodynamic pressures.

In the two following parts, validations are shown for a navy ship and for an FPSO, by comparing stresses recomposed by the conversion matrix approach with stresses directly measured on-board.

3. VALIDATION ON A US COAST GUARDS CUTTER

3.1. Ship model and sensors location

To validate this hybrid approach, the stresses measured aboard a US Coast Guard cutter in the context of the VALID Joint Industry Project (see [5]) are used. The ship was instrumented with three long base strain gauges (LBSG in the picture below), measuring the global deformation, and three local strain gauges (SG in the picture below). SG1 measures the stresses close to an opening, SG2 on a bracket and SG3 on the flange of a longitudinal deck stiffener.

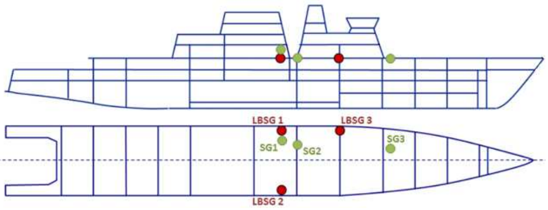

Figure 1 – Stress sensors location aboard the USCG STRATTON

To ensure a good precision of the results, the finite element model was refined in the areas around each sensor, with an average dimension of 25mm for the finite elements.

A first application of the conversion matrix approach for the hybrid monitoring was already presented in [5]. An update of these results is presented here, including a correction of the finite element model in the vicinity of the SG3 stress gauge and a discussion on the choice of the modal basis for the computation of the conversion matrix.

3.2. Selection of modal basis for the computation of the conversion matrix

In the previous study presented in [5], the modal basis used to compute the conversion matrix had been optimized to reconstruct as best as possible the vertical and horizontal bending moments along the ship length. The first mode had been chosen to maximize the vertical bending moment amidships, the following modes being automatically chosen by the software using the methodology proposed in [4].

The modal basis thus obtained is displayed in the three figures below. It was then used to compute the conversion matrix linking the stresses at local strain gauges (SG) to those at long base strain gauges (LBSG).

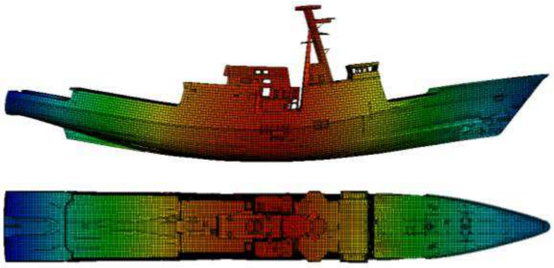

Figure 2 – Base 1, mode 1: 180°, 0.75 rad/s

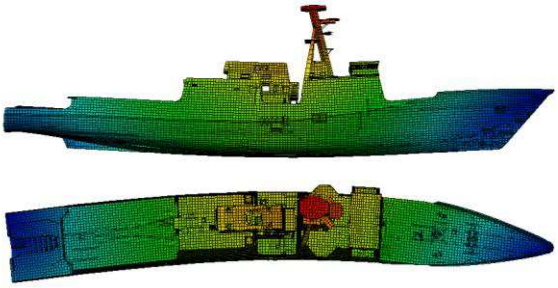

Figure 3 – Base 1, mode 2: 250°, 1.40 rad/s

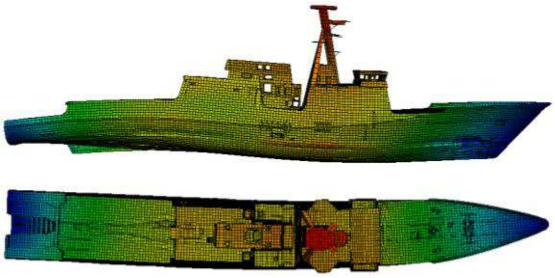

Figure 4 – Base 1, mode 3: 140°, 1.05 rad/s

To analyze the influence of this selection process, a second modal basis is constructed to optimize the reconstruction of long term stresses at the three strain gauges (SG) by the conversion matrix. To achieve this, the first mode is chosen as the one maximizing the stress at the third strain gauge (SG3).

Table 1 – Modal bases

Base	Mode	θ (degrees)	ω (rad/s)	φ (rad)
1	1	180	0.75	2.70
	2	250	1.40	1.11
	3	140	1.05	0.95
2	1	70	1.30	1.87
	2	210	0.85	2.38
	3	140	0.85	2.60

For both bases (the former and the new one), the number of modes is limited to three because there are only three inputs in the system, the three long base strain gauges. The characteristics of the three regular waves defining these three modes are detailed in the table above. The wave headings, frequencies and phases are denoted θ, ω and φ; $\theta = 180°$ corresponds to a head wave, and $\theta = 90°$ to a starboard beam wave.

3.3. Validation of hybrid monitoring

The comparison between reconstructed and measured values is done using data measured on a 5 months deployment. The data has been cut in thirty minutes time windows; for each of these time windows, the conversion matrix is applied to the stresses measured on the three long base strain gauges to obtain time series of stresses reconstructed at the local strain gauges.

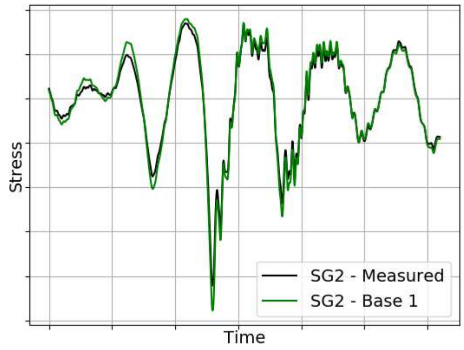

Figure 5 – Recomposition of stresses measured by strain gauge SG2

The figure above illustrates this process by comparing on a 30 seconds time window the recomposed stresses (using the original modal basis) with those directly measured on the local strain gauge SG2. It is noteworthy that the hybrid approach using the conversion matrix can reconstruct the measured signal with a very high accuracy, even including the transient vibrations likely caused by a bow slamming impact.

To sum up the results on the 5 months measurement campaign, standard deviations are computed on each time window for both converted and measured time signals, and plotted one against the other in the three pictures below.

For each stress sensor, a global indicator of the relative error (denoted $rRMSE$ for relative root mean square error) between converted and measured standard deviations is also computed:

$$rRMSE = \frac{\sqrt{\sum(x-x_{ref})^2}}{\sqrt{\sum x_{ref}{}^2}} \qquad (6)$$

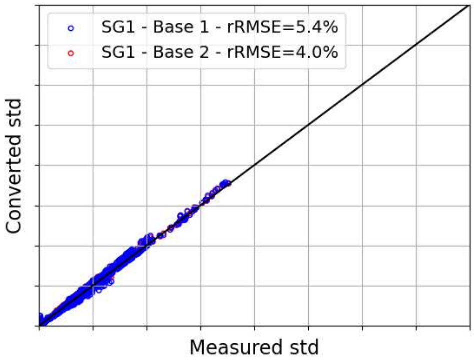

Figure 6 – Stress standard deviations; SG1

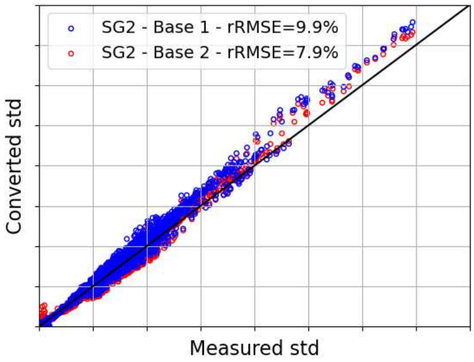

Figure 7 – Stress standard deviations; SG2

The global performance of the hybrid monitoring approach is very good for both SG1 and SG2 stress gauges, with values of relative errors less than 10% for both modal bases. For SG3, the results obtained on the first modal basis, optimized to reconstruct the bending moments, overestimates the stresses with an overall relative error of 22%.

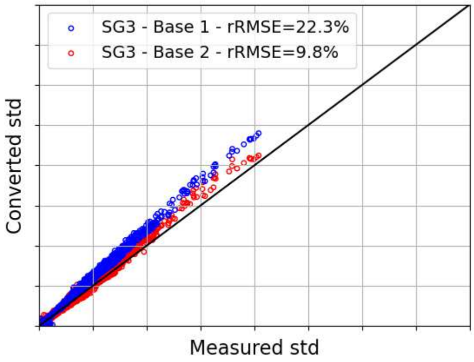

Figure 8 – Stress standard deviations; SG3

On the other hand, the results obtained with the second modal basis, optimized to reconstruct the local stresses, give much better results with an overall error of 10%.

The choice of the modal basis is clearly the major issue with this approach based on the conversion matrix concept. However, making a more relevant choice for the first mode of the basis and for the optimization criterion (stresses rather than bending moments) results in a very good match between recomposed and measured stresses.

3.4. Application for the monitoring of cumulative fatigue damage

Once the time signals of stresses in the structural details are reconstructed by the conversion matrix, the stress cycles can be counted for each of the 30 minutes time window using a Rainflow algorithm.

The cumulative damage can then be computed using the Miner sum and an appropriate S-N curve. This could then allow the real-time monitoring of the structural health of the structure as shown in the picture below, where the cumulative damages computed at the three strain gauges are compared. In this example, a simplified S-N curve was used with only one slope ($m = 3$).

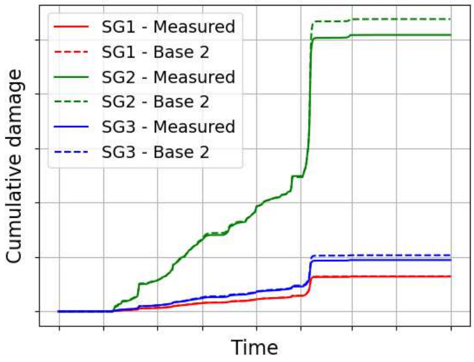

Figure 9 – Cumulative fatigue damage

4. VALIDATION ON A SPREAD MOORED FPSO

4.1. Ship model and sensors location

The second example for this article is a spread moored FPSO operating off the coast of West Africa, instrumented with an Advisory Hull Monitoring System in the context of the MONITAS Joint Industry Project (see [3]). In a recent conference article, the possibility to use measured or computed wave spectra to perform a virtual structural health monitoring was analyzed (see [10]).

The FPSO is instrumented with strain gauges at two frames, located around 35% (frame 105) and 50% (frame 150) of the ship length. Each frame is symmetrically instrumented: each side has a long base strain on the deck gauge (LB01, 03, 09 and 11 in the picture below), measuring global deformations of the structure, one local strain gauge located on the flange of a side shell longitudinal stiffener (SG05, 07, 13 and 15 in the picture below) and one local strain gauge located on a stringer close to the ballasts (SG06, 08, 14 and 16 in the picture below).

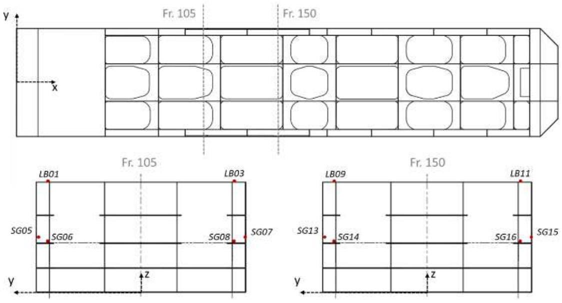

Figure 10 – Stress sensors location aboard the FPSO

In this article, the focus is set on the long base strain gauges installed on the deck, for which the conversion matrix approach is used; the results are then compared to those obtained with virtual hull monitoring (see [10]) using wave spectra directly measured by a buoy.

The stresses in the deck are computed with a full ship finite element model. Secondary stiffeners are modelled by beam elements and steel plates are modelled by one plate element between each secondary stiffener.

4.2. Selection of modal basis for the computation of the conversion matrix

In this example, the goal is to recompose the stresses in each of the four long base strain gauges based on the three remaining sensors.

In each case, the modal basis is limited to three modes, and is optimized to recompose as best as possible the stresses in the targeted long base strain gauge. Two strategies are tested for the choice of the first mode, each time taking into account the on-site wave conditions by limiting the waves to following seas. For each of the four sensors, the first basis is selected by choosing the first distortion mode as the following wave ($\theta = 0°$) maximizing the vertical bending moment. The second basis is selected by choosing the first distortion mode as the one maximizing the stress at the targeted LBSG in a plus or minus 60° with respect to the aft of the FPSO. For the two bases, the remaining two modes are then automatically chosen using the methodology proposed in [4]

To illustrate this, the table below details the three modes chosen for both bases to optimize the reconstruction of stresses in the LB01 sensor.

Table 2 – Modal bases for LB01 sensor

Base	Mode	θ (degrees)	ω (rad/s)	φ (rad)
1	1	0	0.4	2.76
	2	130	0.55	1.75
	3	220	0.55	1.65
2	1	50	0.55	2.06
	2	230	0.6	1.84
	3	350	0.45	2.03

4.3. Validation of hybrid monitoring and comparison with virtual monitoring

30 months of measured data are available for this comparison. After filtering the time windows to only keep loading conditions close to the one used in the finite element model of the structure, only 30% of the data is considered (approximately 11700 thirty minutes time windows).

In the recent study (see [10]), virtual monitoring was validated by using stress transfer functions computed by hydro-structure simulations and by comparing several sources for wave spectra:

- Measurement of two-dimensional (frequency and direction) wave spectra by a buoy nearby the FPSO
- Computation of two-dimensional wave spectra by hindcast ocean model
- Simplification of the spectra by analytic models describing the frequency and directional spreading

In this paper, the results of the conversion matrix approach are compared with the results obtained from the measured wave spectra, which gave slightly better results than the one obtained from the hindcast model.

The same post-processing as with the USCG cutter is performed: on each thirty minute time window, the standard deviation is computed for the measured, converted (hybrid monitoring) and computed (virtual monitoring) values, and compared in a scatter plot. The global relative error is also computed ($rRMSE$, see equation (6)).

The four pictures below show that the hybrid monitoring based on the conversion matrix approach gives good results for the comparison of stress standard deviations. For each sensor, the recomposed values are closer to the measured ones than the values computed by the virtual monitoring, independently of the modal basis.

It is particularly interesting to notice that the dispersion with respect to the measured values is much less for the hybrid monitoring compared to the virtual monitoring.

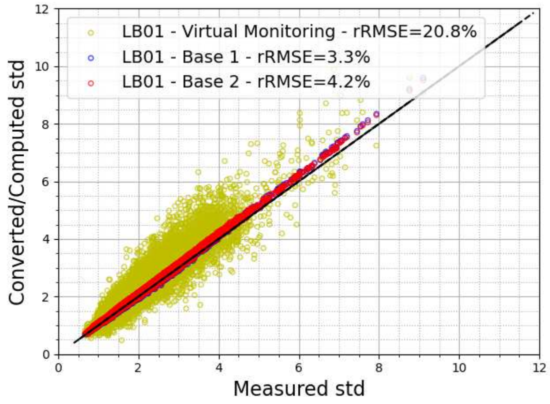

Figure 11 – Stress standard deviations; LB01

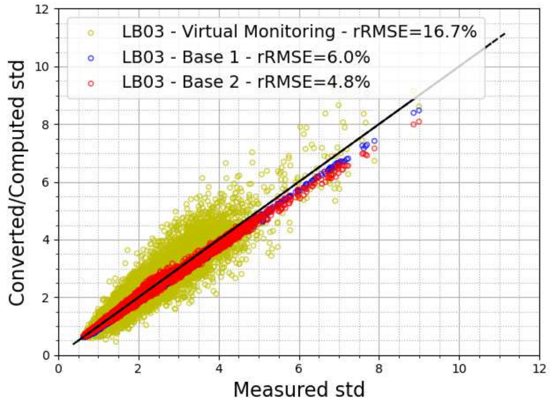

Figure 12 – Stress standard deviations; LB03

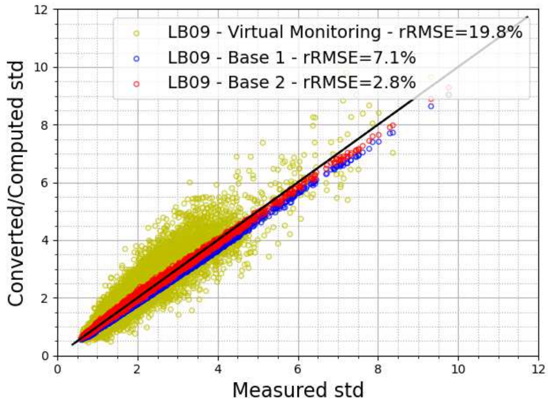

Figure 13 – Stress standard deviations; LB09

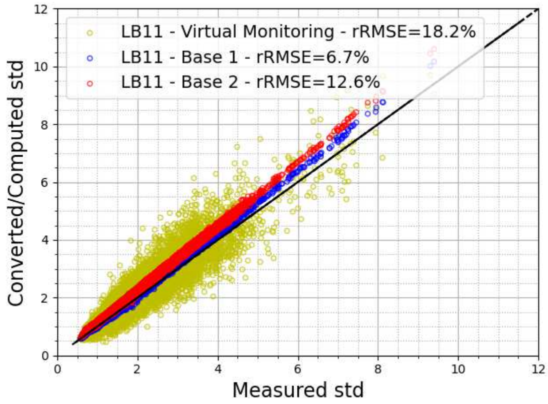

Figure 14 – Stress standard deviations; LB11

Finally, the cumulative fatigue damage can be computed by counting the stress cycles with a Rainflow algorithm and applying an S-N curve and the Miner sum.

The conclusions here are basically the same as when comparing the standard deviations, at least for the first three sensors. The cumulative damages computed by the hybrid monitoring are still better than the ones computed by the virtual monitoring.

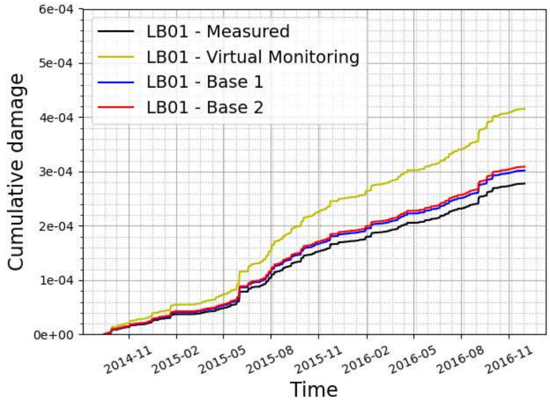

Figure 15 – Cumulative fatigue damage; LB01

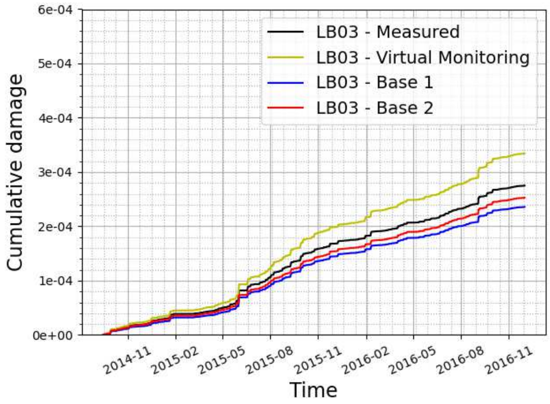

Figure 16 – Cumulative fatigue damage; LB03

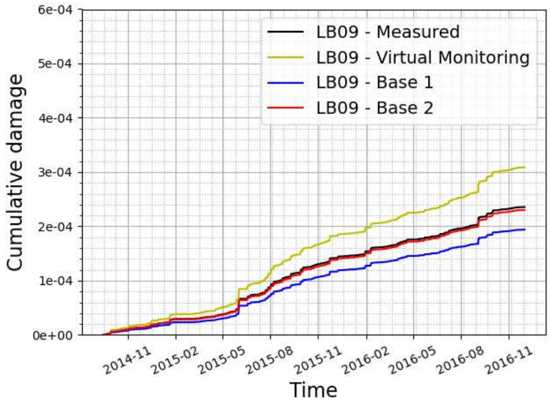

Figure 17 – Cumulative fatigue damage; LB09

The same cannot be said for the fourth sensor (LB11), for which the performance of the virtual monitoring is slightly better than with the conversion matrix approach. This is especially the case for the second base that showed a higher global error (12.6%). In this case, the constant bias brought by the method results in a larger difference for the cumulative fatigue damage, although there is less scatter in the standard deviations.

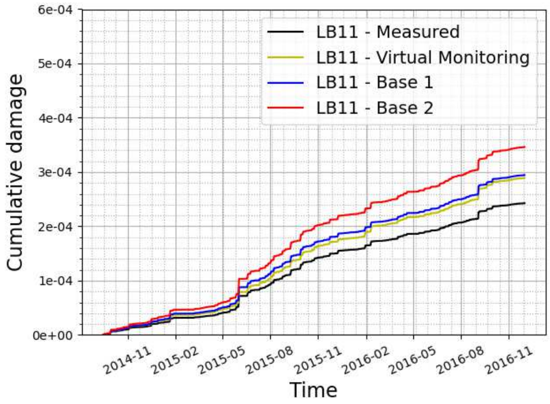

Figure 18 – Cumulative fatigue damage; LB11

The good performance of the conversion matrix approach should of course be moderated here. The application case could indeed be qualified as an "easy" one: the three LBSGs acting as input mainly measure global bending effects, and the conversion matrix only tries to recompose those same global effects as seen by the fourth LBSG.

Further analyses are on-going to extend this comparison to other sensors measuring stresses on the side shell stiffeners and on the stringers; in other words, sensors much more prone to local effects than the sensors on the deck.

5. CONCLUSION

On top of the classic approach to monitoring, consisting of directly measuring the physical values of interest, two digital approaches can be used:

- Virtual monitoring based on a whole chain of numerical computations, from wave spectra, to hydrodynamic pressures and finally structural responses.
- Hybrid approach combining directly measured stresses and digital model of the structure through the conversion matrix approach.

The classic approach is the most precise, the only uncertainty being the one from the sensors themselves, but it is rather limited in terms of reach: structural details far away from the sensors cannot be monitored.

The virtual monitoring is not affected by this limitation: structural response can be computed everywhere; however the precision is not as good because each numerical simulation brings its own uncertainties.

Finally, the hybrid approach takes advantages of both the physical and digital worlds: it ensures a good precision by using directly measured values as input, and allows the monitoring of all structural details thanks to the digital model of the structure.

Two validation cases have been presented. First with a USCG cutter instrumented within the VALID project: the measured data was used to show the good recomposition of the cumulative fatigue damage in the three structural details. Then with a spread-moored FPSO instrumented within the MONITAS project: the virtual and hybrid approaches were compared, the hybrid monitoring giving better results than the virtual one (especially when looking at the scattering of converted/computed stresses compared to measured stresses).

Other validation are of course necessary and are still the object of research projects, especially for the case of structural details subjected to local loads.

6. ACKNOWLEDGMENTS

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