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INFLUENCE OF OCEAN TRANSPORT ON THE DESIGN OF ONSHORE AND OFFSHORE CONSTRUCTIONS, MODULES, TOPSIDES, JACKETS AND TOWAGE ON FPSO DESIGN

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ABSTRACT

Oil and gas installations both onshore as well as offshore are often built in modules and components on a different location than where those facilities are commissioned. Although stress and fatigue damage have proven to be significant on these structures during ocean transport, ocean transportation is often not adequately accounted for during design. Prior to arrival on its final destination, constructions are exposed to severe motions when carried on a modules carrier, a general purpose vessel or towed by 1 or more ocean tugs. The authors argue that calculations on the significance and effect of these motions should be based on proper motion response calculations instead of currently used ‘rules of thumb’. Especially regarding the continuing growth of the size of these carriers and the weight of the structures which both increase the negative effect of sea behavior and affects the loads on the constructions. This article aims to explain the importance of design for transport during the design-phase of these onshore and offshore structures. A distinction is made between structures transported aboard a barge, semi-submersible or general purpose vessel and floating structures transported through a ‘wet-tow’ operation.

1. INTRODUCTION

Large on- and offshore constructions are commonly built in places distant from their actual location of use. This requires large ships to transport these constructions (e.g. topsides, jackets, JU Rigs, chemical processing modules, wind turbine parts) over sea. Shipbuilding engineers are aught to be familiar with the effects of waves and hydrodynamic forces on the hull and construction of a ship. Ships are built to resist these forces and last its minimum fatigue life suffering from continuous and varying types and magnitudes of hydrodynamic stress.

In contrary to this common practice in ship design, effects of motions due to sea behavior are not accounted for during the design of the constructions mentioned earlier. Because of their significant weight and size they are exposed to the same motions and fatigue damage as the ship which is transporting it. The effects of these motions become even more significant when a ship’s size increases. The increasing use of larger ships due to profitable economies of scale makes a thorough analysis of motion response behaviour even more important and therefore add to the extra practical relevance of this paper.

Identical problems are experienced on floating constructions too big or too heavy to be transported aboard a ship. These types of constructions are - given their ability to float - towed to their destination. Examples are FPSOs (Floating Production & Storage units) and FLNGs (Floating Liquid Nitrogen Gas units). These units, usually barges or ships destined to process, store and offload oil or gas are usually designed for their operating purpose only. Not enough attention is paid to transportation, often resulting in expensive last minute design changes or repairs.

The remaining of this paper will focus on explaining the importance of taking into account issues regarding transportation of constructions over sea and implementing these lessons in the design phase of the structure. A distinction is made between dry-transport (or dry-tow) operations and the much weightier wet-towed FPSOs and FLNGs and their specific problems.

2. NOMENCLATURE

a	Acceleration
A	Area
c(x)	Force due to current on the catenary
CoG	Centre of Gravity
CPC	Cargo Planning Computer
C_θ	Drag coefficient of the towing wire
D	Cumulative fatigue damage
dD	rate of damage accumulation
FAMON	Fatigue monitoring system
FEED	Front End Endgineering and Design
FPSO	Floating Production, Storage and Offloading unit
F_w	Resistance
g	Gravity
GBS	Gravity Base Structures
HMC	Hydrographic and Marine Consultants BV
HULLMOS	Hull Monitoring System
Hz	Hertz
IACS	International Association of Classification Societies
JU	Jack Up
L	Length
LCG	Longitudinal centre of gravity from App [m]
MARIN	Maritime Research Institute the Netherlands
MQK	Marine Quality Kit
RAO	Response Amplitude Operator
SACS	integrated finite elements analysis suite
SafePlan	Strain analyses and fatigue engineering safety system
SHIPMO	Motion response program
TCG	Transverse centre of gravity positive to port [m]
TNO	Netherlands Organization for Applied Scientific Research
v	Speed
VCG	Vertical centre of gravity from base line [m]
y	Deflection
$\Delta\sigma_i$	Stress range [MPa]
ρ	Specific weight of water
θ	Angle between the towage-wire and the water plane

3. BACKGROUND

The lead author of this article has been involved in transport engineering projects for over 30 years. Within its current engineering & consultancy firm HMC it advises shipping companies' engineering departments and owners of the mentioned structures on the technical part of these projects. It is important to prepare modules for transport. This must be addressed already in the FEED phase of any project. This paper is written on the foundation of the experience with these problems and aims to make all parties aware of the importance of involving transport engineering in the design phase of on- and offshore structures.

The main cause of much of these problems is the unjust use of 'easy' methods of calculation: Rules of thumb regarding design for transport. An example is the 20/10 rule used by a great part of the industry. In calculations to secure cargo on a ship one tends to use 20 degree roll with a roll period of 10 seconds as guideline. However, in today's ships classified as open stern module carriers with extreme beam and small length over beam ratio close to 3, 35 degree roll with a periods of 20 seconds are not uncommon. The transport industry rejects the continuing use of these rules of thumb, as we are perfectly capable of calculating such motions.

The main aim of this paper is therefore to shed light on the importance of involving transport engineering in the design phase of structures, even in the FEED phase. The paper describes two real life cases of the consequences due to lack of attention to engineering issues during ocean transport. Based on these and other examples solutions to measure and prevent such cases are proposed. The paper will round up with underlining the importance of taking transport engineering into account in the early stages of design and construction of modules to be transported across oceans.

4. RESEARCH DEVELOPMENT AND INNOVATION IN TRANSPORT OF MODULES

Sensitive, heavy and bulky cargo with a low stowage factor can be damaged due to fatigue. An investigation of an accident with a JU rig on a dry tow whereby one leg of the rig collapsed, proved that proper sea fastening with wedges would have extended the life time of the leg construction. In the condition during which the accident occurred the lifetime would be lengthened with approximately a factor 100. Loads due to large heeling angles were not the cause of the damage but the accumulation of higher order motions resulted in fatigue damage.

During another transport measurements indicated that the vibrations in the legs of a new JU rig had an enormous effect on the fatigue life of the legs, as such that the rig's legs were at the end of their fatigue life after 3 voyages on a heavy lift vessel [8]. Also in this instance loads due to large heeling angles were not the cause of the damage but the accumulation of higher order motions resulted in fatigue damage.

These are only two examples within the offshore world with undoubted lack of transport engineering effort to prevent such fatigue to accumulate this rapid. At these times, it was not common practice to use software and measurement systems to analyze motions, that's why lessons were learned the hard (and expensive) way. Nowadays, measurement tools and software is readily available to open the black box of fatigue life and analyze what exactly is happening.

When analyzing ocean transport, two broad types of transport can be distinguished: Dry-transport and wet-transport operations. The first involves transport of the focal object aboard a barge or ship, the latter involves transportation of floating objects by towing them through the water.

4.1 Dry-transport operations

During dry-transport operations, a multitude of parties have a vested interest in predicting and determining the amount of stress or fatigue damage on a module or construction during transport: A construction's owner or insurance company to provide proof with arguments against the shipping company in case a structure gets damaged, the shipping company itself or its engineering partner to limit their liability or a construction's fabricator and designer to prove whether the transporter did not exceed specified maximum stress limits by sailing a certain speed or direction.

In pursuit of this wish, HMC regularly performs Finite Element Method calculations and fatigue analyses in order to predict high stress spots and possible locations of failure under certain sea states. This however proves to be extremely difficult considering ship's and structures' complex shape and enormous size. In the development of a complete transport safety system for heavy lift transportation and towages SafePlan is developed.

SafePlan consists of a multitude of software and hardware solutions used to calculate and measure loads on floating bodies and heavy-lift cargo. Recent works under this project involve:

- Development of a mobile strain & motions measuring system called the marine quality kit (MQK) to determine an object's motions, strain and fatigue damage.
- Validation of calculated motions using data during several transports
- Comparison of different motion response programs
- Installation of a hull monitoring system HULLMOS on board of a semi-submersible barge
- Development of a fatigue monitoring system called FAMON.

4.2 Wet-tow transport operations

Although principally different, the same systems can be used for wet-tow operations. Wet-tow operations are described as those in which the focal object is towed while floating itself. Usually, these towing operations involve large FPSOs or FLNGs barges or drilling rigs. To offer an image for one's imagination, see the following picture. This FPSO is towed by three tugs.

Figure 4.1 – FPSO in wet-tow transport

FPSOs are built to do their job: Sit still floating at open waters processing and storing oil. Many times, the design engineers lack the insight of the significance of forces released upon the structures (and vulnerable equipment on board) while in transport. HMC encounters many avoidable problems due to lack of attention to the transport phase. Examples are the lack, or wrong placement of towline connections (inducing unwanted stress during tow), underestimated motions and strains on the hull and equipment aboard and unexpected harsh weather conditions. For wet tows, the same tools can be used to measure the above as in dry-tow operations. Hence we propose the following tools and solutions to be used on dry-tow operations and to these wet-tow operations as well.

In the following paragraphs an outline of SafePlan and two main components (MQK and FAMON) will be given in order to help understand the full extend of its explanatory power in fatigue and strain measurement.

4.3 SafePlan

During the first Marine Heavy Transport & Lift conference the lead author addressed the project Strain Analyses and Fatigue Engineering in Heavy Transportation and Towages under the acronym SafePlan.

During the first phase of the project it had been proven that for the determination of the environmental conditions for transport engineering satellite registrations are reliable.
A method had been developed to determine:

- Metracentric height variation in waves
- Critical GM values and conditions for parametric roll.

For voyage planning measures can be taken to avoid these critical situations.

As a fit example for explaining the real-time measuring value of SafePlan's systems we take the increased need for heavy cargo ships to sail past the Cape of Good Hope off the coast of South Africa. Since the Suez channel has a maximum allowable height of 65 [m], ships with cargo higher than that will have to sail all the way around Africa. This is especially the case for those transporting drillrigs and JU rigs. For the passage of Cape of Good Hope most notorious is the Agulhas Current / Retroflection outside South Africa. The strong current towards the south-west meets swell generated by the frequently occurring storms in the Southern Ocean. It is most likely that reported ship losses and the rogue and steep waves in this area are the result of focusing waves by variations in the current field such as eddies. A stochastic model of this phenomenon exists, and can be further developed to assess risk for transports crossing the area. To reduce risk, a routing service can be developed based on detailed monitoring of the currents and prediction of wave focusing.

In the second phase of SafePlan the following issues have been investigated:

- Integration of explanatory algorithms
- Validation of motion response calculations
- Developing a practical fatigue assessment model.

Measuring local strains on the seafastening of a ship's load during transportation allows the owner to gather and analyze data concerning cumulative fatigue damage. These real-time measurements are not only supposed to reduce maximum effects of statistical data, but diminish the suggested maximum correlation between all the assumptions which come with conventional ways of designing seafastening.

Measurement by the MQK Software specialized in measuring and storing raw stress data gives insight into the local nominal stress range near hot spots on the sea fastening. These results can be used directly for the fatigue damage calculation. The advantage of this procedure is not only that the response due to the natural combination of motions is incorporated, as well the use of real-time weather condition instead of Monte Carlo simulations of the weather and sea condition, the local effects of deflection are incorporated, the uncertainty of mass distribution, and the assumed stiffness of the tubular joints.
All these assumptions and the correlated effects are omitted in the fatigue damage analysis when using the local strain measurement procedure.

The first measurements aboard the Submersible barge form phase 1 of a plan with the ultimate goal to provide a clear and true model to predict fatigue life of offshore structures and measure and monitor real-time data while sailing.
The conclusions of the second phase of SafePlan:

- Calculated motions for the subject transportations were accurate, measurements prove the accuracy of the calculations.
- The fatigue monitoring system, hardware and software, is a useful instrument for fatigue monitoring.

In pursuit of the SafePlan project three more ore less stand-alone applications were born. First of all is the Marine Quality Kit.

4.4 The Marine Quality Kit

In short, the Marine Quality Kit, or MQK, consists of a mobile box carrying a laptop computer, strain sensors and a multi-directional accelerometer. The rest of the box's space is filled with hardware to combine all three elements into one overall measurement system. An option to transmit measured values to a remote laptop (for instance on the bridge) is provided as well.

Figure 4.2: MQK

The MQK can be shipped throughout the world and installed on any given vessel, barge or object to be transported overseas. By relating motions to strain and fatigue, an area of relevant practical insight is accessed through which operators can directly link the practical influence of a sea state to the object of measurement including all variables caused by ship design, age, corrosion and the like. Instead of calculating and modeling, the MQK approaches the problem by fact based measuring.

Strain sensors such as those showed in picture 4.2 are installed on so called hot spots on the structure. These hotspots are determined via modeling and upfront FEM analysis. These analyses show spots with the highest expected stress in a structure under certain given loads. These are the spots you want to be measured during a ocean transport.

Figure 4.3 - Strain sensors mounted on a testing tube

Besides strain sensors, an accelerometer is installed. As long as the actual location and distance between the accelerometer and a ship's Centre of Gravity (CoG) is known it can be installed on any given location on the ship. This is due to the software translating measurement input back to the CoG.

By combining both strain and motion measurement the system achieves the following:

- Real-time measurement of strain data during any given operation
- Ability to change heading and speed of ship to reduce load on object or in case maximums are reached
- Post-hoc analysis of data for reporting on actual strain and fatigue damage.
- Post-hoc proof of loads incurred on structure due to transport for shipping company, owner and warranty surveyor.

Figure 4.4 – Ship during test trials equipped with MQK

The strain sensors and motion sensor (accelerometer) deliver data to the data acquisition and analysis program FAMON. This program writes time traces of the stress levels measured with the sensor and depicts the cumulative damage D and the rate of damage accumulation, dD, as well as the damage increase over the past 24 hours. FAMON enables real-time monitoring and comparison with a priory set maximum stress or acceleration levels. More information on this software package can be read in paragraph 4.5 of this article.

The MQK can offer more accurate ways of determining fatigue life of a structure transported offshore. The following example illustrates the practical struggles of dealing with fatigue problems: The conventional evaluation of fatigue damage on drilling rig jackets is performed with SafeTrans data as input for the determination of the 16 load combinations for each sea state. These load combinations are used as input for SACS (FEM software). The 16 load combinations are used to find the worse case scenario of the theoretical combined motion which results in worst case nominal stress range. This approach is very conservative:

1. Deflection in hogging and sagging condition is calculated for a standard wave in longitudinal direction in which pitch occurs and no roll
2. Maximum pitch occurs in head seas, in that condition roll is zero.

Already in the beginning of sailing with self propelled heavy lift ships similar discussion was negotiated for seafastening that combined loads should be used. Now, the same issues count for fatigue calculations. To work around these problems in a responsible and safe way, two options are put forward:

The first option consists of measurement in 6 degrees of freedom during transportation in CoG. This result will be converted to independent distributed values for each degree of freedom. The same exercise as performed with Safetrans to generate the 16 load combinations is needed to get the input for SACS. The advantage of this procedure is that the real-time weather conditions are used to update the Monte Carlo simulations of the weather and sea conditions. The disadvantage of this procedure is the conversion to independent values of each degree of freedom leading to search for the worst case combination of the 16 load combinations. The natural combination, which was originally in the measured data, will lead to a substantial lower stress range, than the worst case load combination will be used. E.g. The maximum effect due to roll will be combined with the maximum effect due to pitch and the maximum deflection, while maximum roll occurs at zero pitch and no deflection and maximum pitch occurs at zero roll.

The second option asks for measurement of local strains on the seafastening and preferable on the jacket. This is where the MQK comes in. Instead of modeling and conservatively guessing, the MQK allows strain and fatigue to be measured. During transportation the MQK gives direct insight into the local nominal stress range near the hot spots. These results can

be used directly for the fatigue damage calculation. The advantage of this procedure is not only that the response due to the natural combination of motions is incorporated, as well as the use of real-time weather condition instead of Monte Carlo simulations of the weather and sea conditions, the local effects of deflection are incorporated, the uncertainty of mass distribution, and the assumed stiffness of the tubular joints.
All these assumptions and the correlated effects are omitted in the fatigue damage analysis when using the local strain measurement procedure.

The real-time measurements are not only supposed to reduce the maximum effects of statistical data, but diminish the suggested maximum correlation between all the assumptions as well.

The following figure schematically shows the simplification of data analysis. On the bottom left side two options are given. The first, using measured data as input for SACS, and the second, measured and calculated directly.

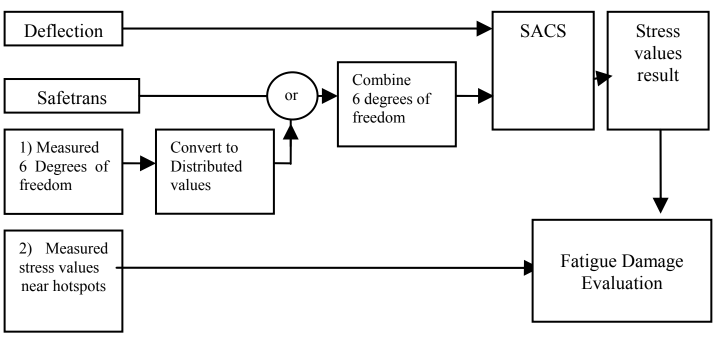

Figure 4.5 – Schematic overview of fatigue analysis methods

The locations for fitting the sensors are proposed based on the damage ratios as calculated in the design calculations for jacket transportation.

However, some owners prohibit welding of any kind to their structures after delivery of the constructs. In this case two alternatives are offered: Measurement by fibre optic bragg technology sensors, or measurement on non-tubular seafastening. The first option exceeds the aim of this article. The second option is a realistic alternative to measuring on the jacket itself.

Besides cargo measurements, it is also possible and highly advisable to keep an eye on a ship's own fatigue life and strain damage. Therefore, and using the same technology, HULLMOS has been developed. In general, HULLMOS can be seen as a non-mobile version of the MQK. Albeit it consists of different sensors and data gathering equipment, the output is identical. Describing HULLMOS in further detail exceeds the aim of this paper and will thus be concluded with this notion.

4.5 FAMON

Both the MQK and HULLMOS systems are used to measure strain and motions. To interpret, process and analyze the raw data from these measurement systems, FAMON (Fatigue Monitoring) is used. FAMON is able to combine motions and strain data, apply rainflow analysis and reduce data to the necessary variables (e.g. stress cycles for fatigue versus maximum strain amplitude for comparison with maximums) In short: FAMON processes raw bulky data into interpretable output. Within SafePlan, FAMON allows raw actual data to be compared with predicted data by FEM and SafeTrans analysis.

4.6 Results and advantages

The joint use of FAMON and measuring devices such as the MQK on several transport engineering projects resulted in the overall insight that sometimes fatigue damage is inflicted upon heavy lift structures transported over sea which can be prevented with minor transport engineering efforts.

The use of these systems resulted in several implications and insights. A couple of which is mentioned below. In general, using data of past and future transports measured on board of heavy lift cargo vessels will further enhance quality of motion calculations by providing feedback to and a deeper understanding of the models made upfront.

Besides direct fatigue damage insights the measured sea behavior of the semi-submersible resulted in ideas about possibilities to optimize efficiency by changing the hull design. The measuring systems triggered a study to optimize the bow in order to:

- Improve the seabehavior and achieve a higher sustained speed in waves
- To reduce the bunker consumption considerably
- Reduce spray and wave making resistance.

Another example of the importance of measuring strain and motions is the ability to gain knowledge of unknown behavior on specific sea states: Important reasons for accidents are resonance, resonant roll, broaching and parametric roll. Ships in waves can have a negative stability due to the fluctuations in the shape of the underwater ship, when the ship is in following seas this instability can last long enough that the ship can list and damage can occur.

Although insight is gained in the actual behavior of ships and the damage to heavy lift cargo compared to models, there is always room for improvement. One problem encountered is the need to weld the sensors into place. As mentioned before, this is sometimes prohibited by the owner of the structure. A possible solution could be the replacement of those sensors with optic Fibre Bragg technology. This however, is an area for further research.

5. CONCLUSIONS

In this paper, the authors have explained a continuing problem with increasing effects due to the increasing size of module carriers. These problems become especially relevant on large open stern carriers with extreme beam and small length over beam ratio. This often results in very stiff seabehavior. Both in wet-tow and dry-tow operations motions and strain analysis are often not accounted for during the design phase of an offshore structure. Executing these analyses in the FEED stage of a project will allow the users to avoid expensive revisions of drawings and designs in the very last minute or even during the build process. These last minute design alterations are inefficient and expensive, and above all, cause delay or the possibility of failures and dangerous situations, or at least an unwanted head start on a structure's fatigue life. This can easily be sidestepped by timely intervention during the structure's design phase. The message the authors want to give to the offshore industry is simple: Take care of transport engineering already during the design phase. Don't let it come down to last minute adjustments to reinforce a structure against the rugged life at the open ocean. Often times, this is neglected because engineers tend to fail to see the significance of forces during transport upfront. The MQK and FAMON help make these forces more tangible. This is no longer an area for guesswork by rules of thumb. The industry now has the systems to measure and give feedback to FEM analysis, reducing the number of assumptions that have to be made.

The development of these systems started many years ago, when we first encountered these problems. Via this article, the authors wish to express their concerns in the continuing use of these rules of thumb, especially in light of other possibilities available to engage the problem. The offshore and shipping industry is a highly innovative and competitive industry. Why wouldn't we open up the black box of transport of heavy lift cargo and find out what more is possible?

6. LITERATURE

[1] Recommended Practice, Det Norske Veritas, Dnv-Rp-C203, Fatigue Design Of
Offshore Steel Structures, August 2005
[2] http://en.wikipedia.org/wiki/Rainflow-counting_algorithm
[3]Report No. 13699-6-RD, MARIN order No. 13699.
[4] Bos, A.J M. Sc. MBA Eur. Ing and Melger, F.J. M. Sc, Marine Services Tool based on satellite observations, August 2004.
[5] IACS, Fatigue assessment of ship structures, Nr 56, July 1999.
[6] Wolf B., Ship Stability Safety System, Graduation thesis performed at HMC, June 2003.
[7] Magnuson Allen H., Ph.D., P.E. A reanalysis of barge roll motion data, OTC, May 1007.
[8] HMC/ MARIN research project MOST 2, MARIN report 13286-4-YM Neddrill TRIGON/Mighty 3 Transport monitoring, May 1997.
[9] HMC/ MARIN research project MOST 2, Monitoring offshore and special transports, waves derived from ship motions, MARIN report 13286-2-SE HMC 95647 January 1997

