Assessment of ultimate strength of a typical truss Spar using nonlinear finite element analysis

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Abstract: This paper investigates the ultimate strength of a typical truss Spar platform subjected to characteristic hydrodynamic loads using nonlinear finite element analysis with ANSYS. Material nonlinearities are taken into account without giving consideration to geometrical nonlinearities and geometrical imperfections. Main concerns of ultimate global strengths analysis are initial failure place and final collapse states of the whole platform. It can be found that final collapse modes of Spar platform are closely related to corresponding characteristic hydrodynamic responses. Simulation results are discussed and checked by DNV rules. According to failure mechanism of the object platform, ultimate limit state formulations are developed. Performing progressive collapse analysis of truss spar can provide a better understanding of structure behaviour of typical truss Spar under extreme wave conditions. This paper is hopeful to be a good reference to the ultimate limit state of typical truss Spar platforms under characteristic wave load.

1. Introduction

Nowadays it is common practice to carry out global strength analysis of offshore structures due to emergence of novel and complex designs. These kinds of designs usually have a great difference in structure behavior with those which are proved and already operating for a long time.

A variety of methods such as the simplified method (Smith’s method), the idealized structure method (ISUM) and finite element method have been developed during the past decades for the estimation of the hull girder ultimate strength. The applications of nonlinear finite element method are very few due to the great demand on the computer resource and manpower especially for large scale model. However, the rapid development of the computer technology makes it possible to carry out the nonlinear finite element analysis for the ultimate strength of floating structure with reasonable computation cost and proper modeling. This paper presents a study of such analysis and the whole process is illustrated with a typical truss Spar platform.

Wave-induced responses of offshore structures have been studied extensively for several decades. Wang and Berg etc. (2001) provides an overview of the Truss Spar structural design with emphasis on the design and analysis of the truss structure based on practical design experiences focusing on the methodologies and procedures using random wind and wave time domain analyses. He and Wan (2001) developed a simplified procedure for predicting the ultimate strength of hull girder. Lee and Moan etc. (2008) described global loads and structure response analysis of a prototype semisubmersible and perform global strength analyses of the object platform. Ultimate strength of ships and offshore structures is a broad question and many papers have been published. Cui (2005) presents a simplified pushover method to calculate boat longitudinal strength which is especially
useful for solving analysis of ultimate strength of damaged ship hulls and verify its validity by model tests. Paik (2008) conduct some benchmark studies on ultimate limit state assessment of marine structures by (unstiffened) plates, stiffened panels, and hull girders of ships levels. Different finite element software packages were used to make ultimate limit state assessment of these structures and simulation results were compared. Finally, the ULS level responses that are capital cost indicators for both FWT alone and for the STC system are estimated and compared. To investigate responses of the STC system as mooring tension, spar-tower interface bending moment, end stop force, and contact force at the Spar-Torus interface under extreme conditions Muliawan etc. (2013) performed coupled (wave-and wind-induced response mooring) analysis using SIMO/TDHMILL in the time domain.

Ultimate limit state (ULS) of Spar platform can be classified by global mode, local mode and interaction of these two modes generally due to complication of structure behavior and variation of load conditions. A series of load conditions should be under consideration. From a mechanism view, failure causes of Spar platform include fatigue and fracture, buckling, yielding, corrosion etc. Each type of failure problem can occur alone and it is more common that two or three kind of failure problems have interaction with each other. The consequences of strength failure are disastrous. A concrete example is Alexander L. Kiell killing 123 people.

This study presents a finite element analysis method for the estimation of Spar platform ultimate strength after providing a brief summary of global strength analysis for floating structure. To investigate the ultimate strength of a typical truss Spar platform using the finite element code with ANSYS. A numerical model is built up with the finite element code with ANSYS. The ultimate strengths are evaluated according to characteristic hydrodynamic responses of Spar platform. The nonlinear finite element analysis provides a lot of information about the ultimate strength and collapse mode. Theoretical response descriptions from classification society (DNV, 2012) can be clearly captured by the nonlinear FE analysis. Some design suggestions are recommended and limit state formulations are developed. The results of the nonlinear FE analysis are hopeful to be a good reference to the analysis of ultimate strength of Spar platform.

2. Method for Ultimate Limit State Assessment

As to assessment of ultimate limit state of structures, progressive collapse methods is used which including the simplified methods (Smith’s method), the idealized structural unit method (ISUM) (Ueda et al. 1984) and finite element method etc. Smith’s method and the idealized structure unit method have been used widely to assess ultimate hull girder strength of ships. Through ultimate limit state assessment, interaction between structure components can be taken into account without assumptions adopted in other methods. Nonlinear finite element method is employed in the present paper using software package ANSYS.

Progressive analysis of Spar is quite different from that of ships due to configuration of the whole structure. To assess ultimate limit states of Spar platform, analysis methods for floating structure should be reviewed and method for ultimate strength assessment is similar to some extent.

2.1. Overview of global FE-analysis for floating structure

The intention of global FE-analysis is to assess structure responses resulting from global loads. It is a very time consuming technique and the following steps should be taken: (1) Generation of a global finite element model; (2) Generation of loading condition and design wave load cases ;(3) FE-calculation ;(4) Calculation evaluation; (5) Drawing conclusions.

2.2. Ultimate limit state assessment procedure of Spar

Method for progressive collapse analysis process of Spar platform follows global FE-analysis steps for floating structure to some extent. The distinctions of two procedure is in that the load of global FE-analysis should be determined before analysis and that of progressive collapse analysis will be determined after analysis. Analysis procedure of global FE-analysis method for floating structure is
available to ULS assessment of Spar. This section will provide detail global FE-analysis steps for process of progressive collapse analysis.

2.2.1. Finite element model
Software packages such as ANSYS, ABAQUS and SESAM etc. are widely accepted as structure analysis software to generate finite element models. Global FE-models usually should be built up with three-dimensional shell model to represent the global stiffness. Emphasis should be placed on the structure connections. These connections have great significance to the platform structure behavior and should be built with sufficient stiffness. Global model consist of a big amount of input data and the model should be checked frequently to keep it right. The detailed information of global FE-model of the object platform will presented in the next sector of this paper.

2.2.2. Load generation
The most significant environmental loads for Spar are normally those induced by waves. Several kind global responses to wave load are usually governing for the global strength of Spar platform and characteristic of these wave responses are showed in Fig.1. For these loading conditions design wave load cases have to be created which need to meet the requirements given in rules or values coming from direct load calculation. In survive condition, wave loads condition including global bending moment, maximum acceleration and maximum global shear force etc. are most critical.

Wave loads on hull structure should be calculated by hydrodynamic software packages. Among others, WAMIT, SESAM, AQWA, HYDROSTAR are well known in offshore industries.

To generate wave loads, a hydrodynamic model should be built. After generation of wave loads, selection criteria must be decided such as the maximum values of sectional forces and moments, specify which waves have to be chosen for the global analysis. Some thousands of wave parameter combinations are scanned to select the worst load cases. About load cases for each kind of condition such as survival conditions, operation condition, transit condition etc. are taken as the most unfavorable load cases for the finite element calculation according to characteristic hydrodynamic responses. The focus of this paper is the platform in survival conditions.

2.2.3. Calculation
Three types of load effects including external pressure loads, mass-acceleration terms and additional load types should be taken into account. External pressure loads is produced by contact with its environment and mass-acceleration terms resulted from motion of vessel. These two types of load are usually generated by hydrodynamic analysis. Additional loads such as variations in personnel, laydown and other live loads are not included in the motion analysis and generally insignificant for global stress. These loads may be important on local structure. Mass effects are significant to the calculation of floating structure. The following terms should be included: structural mass equipment loads, personnel, stores, fuel, etc. Structure and other masses should be distributed over suitable areas or smeared into the structure mass. Misdistribution of masses will result in unrealistic point reactions. To deal with this problem useful methods such as increasing the density of structure steel by region artificially are adopted, accounting for equipment, etc. Due to assumptions adopted in hydrodynamic analysis, identical masses should be represented in hydrodynamic and structure model should have the same mass matrix and the centroid, second moment of mass about each should also be identical. Quasi-static structure analysis is a relatively simple approach and can provide good predictions of structure response under regular wave conditions. The load cases must be well balanced, which means platform acceleration forces are in equilibrium with forces from water pressure. Calculation of global FE-model is still a computationally demanding despite of many efforts in the development of this technique. During the last decades the demands on strength analyses have been increased rapidly and fortunately the computation capacity has been increased too. Therefore, computation restrictions no longer exist in most cases.
2.2.4. Evaluation
Calculation evaluation of global FE-analysis is according to the rules and standards (DnV 2012) and should cover the following items: (1) Deformations; (2) Stresses; (3) Buckling; (4) Ultimate strength; (5) Fatigue. Not all of items are under consideration when conducting ULS assessment. Deformations, stresses and ultimate strength are the mains concerns for ultimate limit state of Spar platform. Deformation, stresses and ultimate limit state should be in consistence with each other and that is a precondition to gain confidence.

2.2.5. Drawing conclusion
A necessary job of structure analysis is how to present conclusions. Comment on rationality of structure design and recommendations or proposal are always required in this step. Ultimate limit state assessment of Spar platform can provide some insight on the finale collapse state and reveal failure mechanism of the whole structure.

2.2.6. Ultimate limit state assessment procedure
To conduct ultimate limit state assessment, a global structure model should be built first and a hydrodynamic model is built to generate wave load on the structure. After load generation, some thousands of wave parameter combinations will be scanned to select the worst load case. Wave selection criterion such as maximum global bending and shear forces in the hull is adopted. Calculation of the global FE-model and evaluation of numerical results are by means of software package. Conclusions should be drawn about the structural behavior and comment on imperfection of design. Ultimate strength behavior is often affected by various parameters such as initial deflection shape of structure and boundary conditions and load conditions etc. It is especially true for Spar platform. So the whole process of FE-analysis should be strictly abided by. And the more important thing is to verify the numerical results by various means such as a simplified model, comparison with experimental results or numerical results calculated by different software package.

Software package ANSYS is used for structural model and WAMIT is used for hydrodynamic calculation. ANSYS provide a friendly graphical user interface and have powerful pre-process tools, solver as well as post processing tools. WAMIT can give good prediction of hydrodynamic loads on floating structures. If the sea wave is regular, the wave loads on the object platform are proportional to wave amplitude $A_d$. Progressive collapse analysis can be achieved by applying wave amplitude $A_d$ from a small one and increasing it step by step. When the result of one load step cannot be converged, the structure reaches to its maximum strength capacity. Fig.2. shows a typical ultimate limit state assessment process employed in this paper.

3. Global Structural Model
The main structure of the object platform consists of top side, hard tank, truss and soft tank. To predict the structure behavior accurately, a well-represent finite element model is built up with the finite element code ANSYS.

3.1. Material properties and Loading condition
The elastic-perfectly plastic material model is adopted neglecting the effect of strain-hardening. For numerical model, EQ36 is adopted for the whole structure with yield stress $\sigma_y$ of 315MPa, Young’s modulus $E$ of 206GPa and Poisson’s ratio $\nu$ 0.3.

Selection of the most unfavorable wave loads is according to the classification Rules (DnV) in terms of design wave method which is based on stochastic approach. Environment criteria are built adopting wave statistics of South China Sea. For nonlinear finite element computations, four kinds of load cases including global bending moment, global shear force maximum acceleration and maximum shear force around truss structure are used as candidate load cases. Corresponding characteristic responses of these wave conditions are shortly summarized in Table 1.
Table 1  Theoretical responses description for typical design wave

| Design wave type | Characteristic response description |
|------------------|-------------------------------------|
| Maximum Global shear force | This response will normally give the maximum shear force in the hard tank of the platform. |
| Maximum acceleration | This response will normally give the maximum shear force. |
| Maximum local Shear force | This response will normally generate maximum shear force on truss of Spar platform. |
| Maximum Bending moment | This response will normally induce the maximum bending moment on Spar platform |

3.2. Nonlinear finite element mesh modelling

The global FE-model for the object platform is built up with the finite element code ANSYS. Fig.3 shows the model in the present study. The main structure of Spar platform consists of deck, hard tank, truss and soft tank. Global FE-model which shall represent global stiffness of the whole structure should be built with sufficient detail especially for connections of column and truss. As far as element sizes are concerned, simulation time should be under consideration. Fine meshes in critical area should be employed for coarse mesh will cause unrealistically high ultimate strength. However, cost of memory size and computational time should be under consideration.

The mesh size and element type adopted in this paper are based on recommendations of DNV rules. Four kinds of element types (BEAM188, SHELL181, PIPE20, MASS21, COMBIN14 etc.) are used. Table 2 summarizes the detail information of global FE-model. Connections of the object platform are assumed as critical parts. Mesh sizes of other parts of the platform is about 1~1.5 metres. The mesh strategy is assumed to be good enough to capture realistic structure behavior through a continuous verification of check.

According to the DNV rules, the FE-model is fixed using 6 degrees of freedom, 3 vertical restraints (Z), 2 transversal horizontal restraints (Y), 1 longitudinal horizontal restraint (X), adopting com14 element.
Fig. 3 Global FE-model developed for the object platform

Table 2 Details of global FE-model

| Element type | Shell181 | Beam188 | Pipe59 | Mass21 | Total |
|--------------|----------|---------|--------|--------|-------|
| Number       | 39516    | 46128   | 1096   | 978    | 87718 |

Fig. 4. Characteristic hydrodynamic wave loads (a) bending moment (b) truss shear force (c) maximum acceleration (d) global shear force

4. Numerical Simulation

Four cases which are assumed to be representative hydrodynamic conditions have been run according to process for ultimate limit state assessment presented in this article without giving consideration to the effect of geometric imperfection and geometric nonlinear. These conditions are maximum bending moment, maximum acceleration and maximum truss shear force etc. It is observed that differences of collapse modes are evident and quite match to corresponding wave condition. Fig. 5 shows the deformed shapes and von-Mises stress distributions of the platform structure at the ultimate limit state for various types of wave load. The relationships between the section load under 100 return periods and final collapse states of each type are given in Table 3.
Fig.5. Deformed shapes and von-Mises stress distributions of the object platform at the ultimate limit states under regular sea wave (a) ULS of bending moment (b) ULS of truss shear force (c) ULS of maximum acceleration (d) ULS of global shear force

4.1. Discussion of simulation results

Fig.5 shows ultimate limit behavior of the object platform under characteristic wave conditions. It can be found that hard tank is critical parts of the platform and the initial yielding places are always around the middle of hard tank. Yielding expansion is always around the initial yielding regions and stress redistribution behavior is not so evident. To some extents, the final collapse states of the platform are quite similar under different load conditions. Connections of the platform are always plays an important role. It is strongly recommended that concentration of detail design should be focus on connections of each part.

From a designer’s view, to enhance the global strength of Spar platform, the strength of hard tank should be improved. Maximum acceleration state are not cause obvious plastic regions in final collapse state and the final collapse of this state are caused by combination effects of global bending, shear and truss shear. Connections of each part also have great significance of global structure performance and emphases should be placed on these parts for every kind of state.

4.2. Ultimate limit state expression of Spar

Main section forces or bending moment which are assumed to the cause of final collapse of the object platform have great significance to the object platform. Table 3 summarizes ultimate limit capacity of the object platform in comparison to that of 100 return periods (load case1, load case2, load case3, load case4).

| Load case | Section load | 1  | 2  | 3  | 4  | Ultimate limit capacity |
|-----------|--------------|----|----|----|----|-------------------------|
| Global shear force(kN) | 243 | 24.3 | 24.2 | 24.3 | 670.2 |
| Bending moment (kN.m) | 0.287e6 | 0.264e7 | 0.264e7 | 0.220e7 | 0.947e7 |
|----------------------|---------|---------|---------|---------|---------|
| Truss shear force (kN) | 177.9  | 247.8  | 231.8  | 247.8  | 825.5  |

Spar platform can be split into topside, hard tank, truss, soft tank. According to the configuration of Spar platform and final collapse state of each load condition, ultimate limit statement is closely related with section loads of the object platform. It is evident that ultimate limit collapse of each load case is induced by main section load. $S_F$. Ultimate limit state expression for ultimate limit state design is recommended based on main section load $S_F$. From a mechanism view, section loads or moments induced by hydrostatic condition are slim to none. Ultimate limit state expression can be summarized as:

$$Z = R - S$$

$R$ represents ultimate limit strength of shear force, bending moment and $S$ is corresponding main section load.

5. Conclusion

The ultimate strength of a typical truss Spar platform subjected to typical hydrodynamic loads has been investigated using nonlinear finite element method. The progressive collapse of a typical truss Spar platform is investigated using nonlinear finite element analysis with ANSYS according to global FE-analysis method for floating structure. It can be found that ultimate limit states of Spar platform are quite different from that of ships due to configuration of structure. Although it is not recommended to carry out ULS structural assessment of Spar platform in a single model solutions by DNV rules, with the rapid development of computer technology it is becoming more and more available.

The advantage of the progressive collapse analysis is that the failure of individual structure component and their interacting effects can be acquired in the best way. The true margin of structure safety is reflected by comparison of section loads under ultimate limit state and that of certain return period. It is evident that the final collapse modes are consistent with the corresponding wave loads. The initial yielding place of each load condition is always around hard tank. Reinforcement on these regions will improve the global strength of the object platform. Ultimate limit state expressions are recommended. The concept of these expressions can really provide a better understanding on ultimate limit state behavior of Spar platform. The results of the nonlinear element analysis in the present paper can serve as a good reference of ULS of Spar platform checked by the theoretical predictions of Spar platform based on DNV rules.

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