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Effects of Collision Damage on the Ultimate Strength of FPSO Vessels

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Abstract

Floating production storage offloading (FPSO) vessels are movable offshore structures. These structures are designed with large dimensions, and their decks are loaded with several types of equipment. During collision damage, the hull and deck parts loaded with equipment are severely affected. Therefore, the ultimate strength of FPSO vessels should be thoroughly checked and evaluated. The objective of the present study is to analyze the ultimate strength of FPSO vessels against collision damage characterized by hogging and sagging under longitudinal bending. The cross section of an FPSO vessel is modeled with elements composed of stiffened and unstiffened plates. The vessel length is assumed to occupy one frame space. The ultimate strength of FPSO vessels against collision damage is determined by performing a numerical analysis under hogging and sagging conditions. Multipoint constraint is applied to both sides of the cross section, and the material properties are set to be constant. Collision damage is represented by the loss of element stiffness, and it represents the percentage of the ship's depth. For the extent of transversal damage, B/16 is set to be constant. The minimum and maximum collision damages are taken as 10% and 60% of the ship's depth, respectively. Numerical results show that the ultimate strength of FPSO vessels and their bending stiffness decrease under collision.

Abstrak

Pengaruh Kerusakan Tubrukan terhadap Kekuatan Kapal FPSO. FPSO adalah *floating production storage offloading*, salah satu struktur offshore dengan karakteristik bergerak. Struktur tersebut didesain dengan dimensi besar yang terdiri dari banyak peralatan di geladak. Ketika tubrukan terjadi, lambung kapal tidak hanya menerima dampaknya, tetapi juga geladak dimana banyak peralatan di tempatkan pada daerah tersebut. Oleh karena itu, kejadian ini harus diperiksa dan dievaluasi untuk kekuatan kapal. Tujuan dari penelitian ini adalah untuk menganalisis kekuatan kapal FPSO yang disebabkan oleh kerusakan tubrukan pada kondisi *hogging* dan *sagging* dalam arah membujur. Penampang kapal FPSO dimodelkan dengan memilki elemen yang terdiri dari pelat dan pelat berpenegar. Panjang kapal diasumsikan dengan satu jarak gading. Kekuatan kapal FPSO yang disebabkan oleh tubrukan dianalisis dengan menggunakan analisis numerik pada kondisi *hogging* dan *sagging*. MPC dtempatkan pada kedua sisi penampang kapal dan properti material dibuat konstan. Kerusakan tubrukan digambarkan oleh hilangnya kekakuan elemen dan merepresentasikan persentasi dari tinggi kapal. Pada arah melintang bagian geladak kapal, kerusakan tubrukan diambil B/16. Kerusakan tubrukan diambil 10% dan 60% untuk nilai minimum dan maksimum dari tinggi kapal secara berturut-turut. Hasil diperoleh bahwa kekuatan kapal yang disebabkan oleh kerusakan tubrukan dengan solusi numerik berkurang termasuk kekakuan lenturnya.

Keywords: FPSO, cross-section, collision damage, hogging-sagging, ultimate strength

1. Introduction

One of the most dangerous accidents that a ship could experience is a collision. Collision becomes increasingly hazardous when a ship's deck is loaded with equipment and experiences hogging and sagging under longitudinal bending conditions. Therefore, collision events must be analyzed in terms of the structural strength criterion.

Using an analytical approach and finite element (FE) analysis, Zhang [1] conducted model-scale and full-scale collision tests to quantify key calculation parameters and to verify the capability and accuracy of the proposed analytical method. Muis Alie [2] analyzed the residual strength of an asymmetrically damaged ship hull girder under longitudinal bending. In the study, the beam FE method was used to assess the residual strength of two single-hull bulk carriers and a three-cargo-hold model of a single-side Panamax bulk carrier under hogging and sagging conditions. Parunov [3] assessed the residual ultimate strength of an Aframax-class double hull oil tanker damaged in a collision. Muis Alie [4] employed a simplified approach to study the ultimate hull girder strength of asymmetrically damaged ships. Liu [5] adopted a simplified analytical method to examine the energy absorbing mechanisms of intact and damaged small-scale stiffened plate specimens that were quasi-statically punched at the midspan by a rigid wedge indenter. The purpose was to highlight the importance of large-scale collision and grounding experiments and to discuss the technical difficulties and challenges in analytical, empirical, and numerical analyses.

Liu [6] also compared two methods on the basis of FE simulations to assess the external dynamics and internal mechanics in ship collisions. One method treats independently the external dynamics and internal mechanics (decoupled method), whereas the other one couples their interaction (coupled method). Campanile [7] applied a modified incremental–iterative method to account for instantaneous neutral axis rotation due to an asymmetrically damaged cross section in collision events. In [8], a reliability analysis of an oil tanker in intact conditions was performed to investigate the incidence of load combination methods on hull girder sagging/hogging time-variant failure probability. Muis Alie [9] conducted a progressive collapse analysis of the local elements and ultimate strength of a roll-on–roll-of ship. In [10], a structural reliability analysis (SRA) model based on a Bayesian belief network (BBN) was proposed for hull girder collapse risks after accidents. A BBN was used to represent the random states of variable risk events after accidents, as well as the dependencies between events. SRA was used to evaluate the failure probability of hull girders for each possible accident condition. The hull girder collapse risk of a membrane liquefied natural gas carrier after grounding was also analyzed. Underwood [11] studied the use of progressive collapse analysis to model damaged box girders for the assessment of structures across multiple frame boundaries. The study showed that although progressive collapse analysis can be applied to the assessment of damaged box girders, implementing the newly proposed assessment enhances the accuracy in the calculation of collapse strength through the capture of the true mode of failure. Prestileo [12] explored the reliability assessment of the hull girder of a crude oil tanker while referring to a scenario in which the ship is exposed to sea loads after damage to the bottom of the hull. A number of possible flooding configurations were examined, with each one caused by a group of damage cases and characterized by different locations and extents. Saydam [13] presented a probabilistic framework for the performance assessment of ship hulls under sudden damage while accounting for different operational conditions. Sudden damage scenarios included grounding and collision accidents. The combined effects of sudden damage and progressive deterioration due to corrosion were investigated. The performance of a ship hull was quantified in terms of ship reliability and robustness.

Floating production storage offloading (FPSO) vessels are mobile offshore structures that are exposed to potential damage, such as collision with other vessels. The analysis of ship damage, particularly for FPSO vessels, is limited. Hence, the present study is conducted to analyze FPSO vessels subjected to collision damage. The effects of collision damage on the ultimate strength of FPSO vessels under hogging and sagging conditions are analyzed. The cross section of an FPSO vessel is modeled with elements composed of stiffened and unstiffened plates. The length of the ship is assumed to occupy one frame space to simplify the numerical calculation. The ultimate strength of FPSO vessels under collision damage is determined by performing a numerical analysis under hogging and sagging conditions. The nonlinear FE method code ANSYS is adopted for the numerical calculation.

The longitudinal bulkhead of a ship is located at the center of the cross section. The cross section is shaped like a box, i.e., it has no bilge radius. The multipoint constraint approach is applied to both sides of the cross section, and the material properties are set to be constant. Collision damage is represented by the loss of element stiffness and denotes the percentage of a ship's depth. For the extent of transversal damage, B/16 is set to be constant. The minimum and maximum collision damages are taken as 10% and 60% of the ship's depth, respectively.

2. Finite Element Modeling

The ultimate strength of FPSO vessels is analyzed using a numerical solution. The nonlinear FE method is applied to the calculation, which includes the behavior of FPSO vessels under hogging and sagging conditions. Hence, the FPSO dimensions are presented. The length, breadth, and depth of a ship are 256.5, 70.2, and 20.7 m, respectively. The ultimate strength analysis is conducted with consideration of three conditions: intact condition, 10% collision damage, and 60% collision damage. The intact condition is characterized by the absence of collision damage to the side shell of the ship's cross section. The Young's modulus, yield strength, and Poisson ratio are set to be 210,000 N/mm^2, 325 N/mm^2, and 0.3, respectively. The quadrilateral 181 shell element is imposed on the model. The FE model of the FPSO with intact condition is shown in Figure 1.

For the collision damage conditions, the cross section of the FPSO vessel is modeled by removing the elements from the area. The multipoint constraint is applied to both sides of the cross section. In the present study, the minimum and maximum collision damages are taken as 10% and 60%, respectively, to simplify the calculation. Other damage percentages were considered by Muis Alie [14] for bulk carriers. Figures 2 and 3 show the 2D and 3D models of 10% and 60% collision damage, respectively.

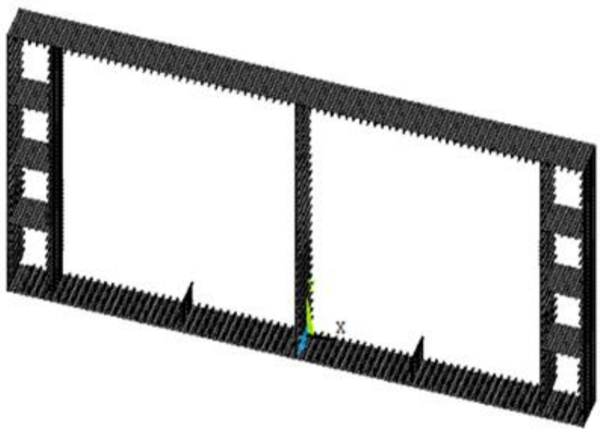
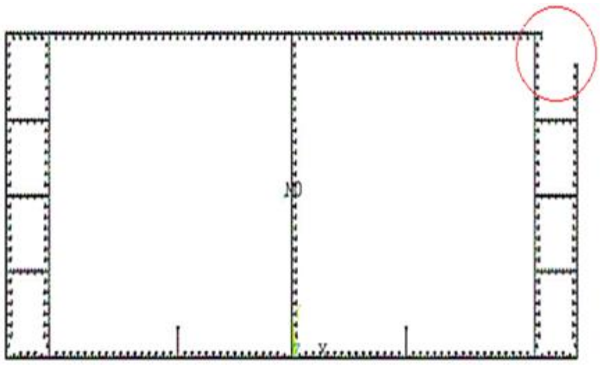
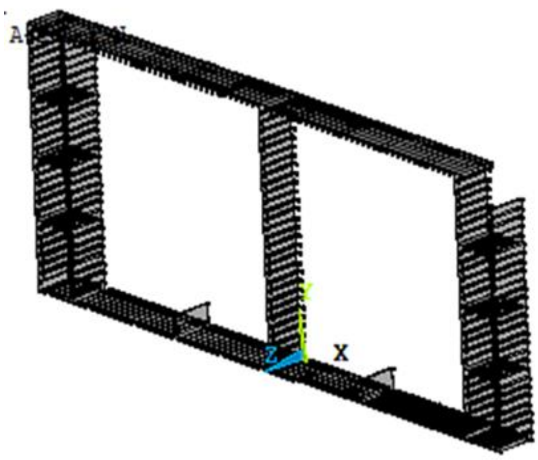


Figure 1. FE Model of Intact FPSO

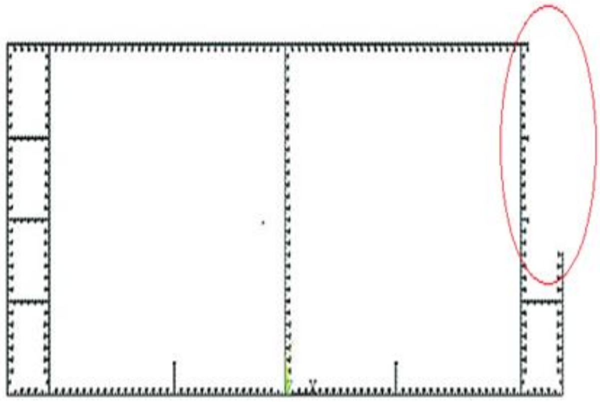


(a) 2D FE Model

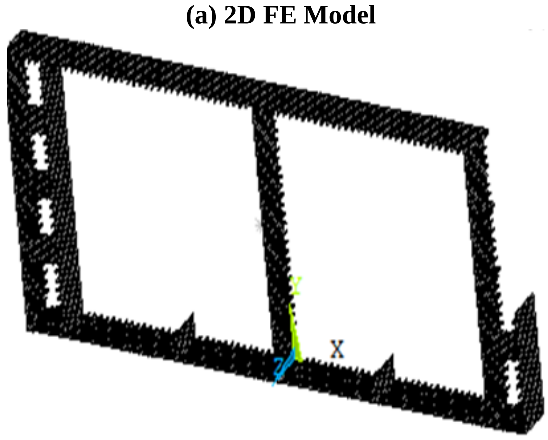


(b) 3D FE Model

Figure 2. FPSO Under 10% Collision Damage



(a) 2D FE Model



(b) 3D FE Model

Figure 3. FPSO Under 60% Collision Damage

3. Results and Discussions

The ultimate strength obtained by the numerical method is presented in terms of stress distributions and moment–curvature relationships under intact and damage conditions characterized by hogging and sagging. Figures 4 and 5 illustrate the stress distributions for intact case under hogging and sagging conditions, respectively. Under hogging, the deck experiences tension, and the bottom part is compressed, as respectively marked by the red and blue colors in Figure 4. Under sagging, the tension occurs at the bottom part, and compression is noted at the deck part. For the intact case, the stress distribution is uniformly distributed along the deck and bottom part.

In [3],[5],6], the ultimate strength of the ship hull girder with damage was analyzed using the FE method. The damage model in these studies is considerably different from that in the present study. However, Muis Alie [14] analyzed a ship hull girder with several collision damages using a three-hold model of a bulk carrier. The longitudinal damage extent was taken as B/16 and kept constant for all damage cases. This parameter is also applied in the present study.

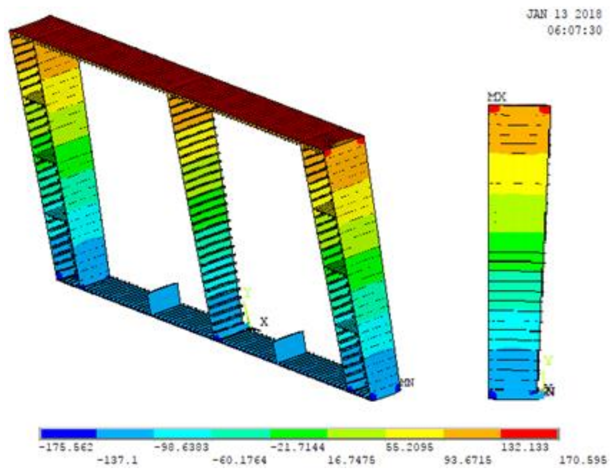


Figure 4. Stress Distribution for Intact Case Under Hogging

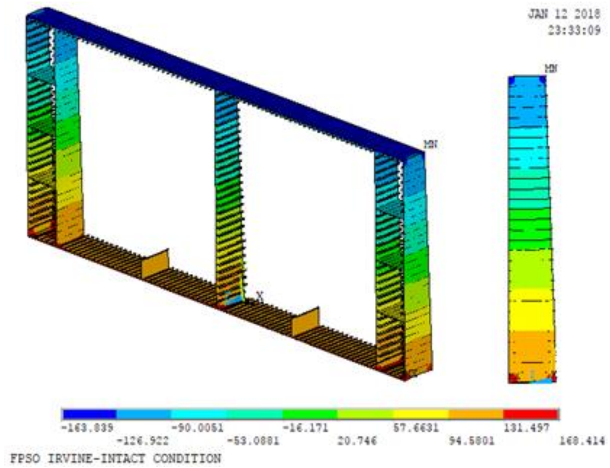


Figure 5. Stress Distribution for Intact Case Under Sagging

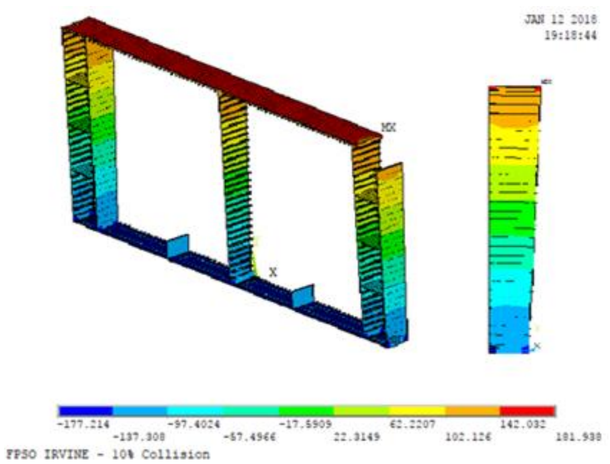


Figure 6. Stress Distribution for 10% Damage Under Hogging Condition

Figure 6 shows the stress distribution for the case of 10% collision damage under hogging. The stress distribution spreads from the damaged part of the deck to the undamaged part. The deck part is under tension, and the bottom is under compression. Under sagging condition, the deck part is under compression while the bottom is under tension (Figure 7). No damage is noted in the bottom area. The maximum and minimum values of the stress distributions are observed at the deck and bottom parts, respectively.

Figures 8 and 9 show the stress distributions for the case of 60% collision damage under hogging and sagging conditions, respectively. The behavior in this case is similar to the stress distribution for the case of 10% damage [14]. The maximum and minimum values of the stress distributions are marked with red and blue colors, respectively.

Collision damages are located not only at the side shell but also at the corner of the deck part. The collision damages are modeled by simply removing the elements at the deck part and side shell. The extent of the vertical damage is represented by the ship's depth. Generally, when collision damage affects at the side shell, the neutral axis rotates along the longitudinal direction [4],[7].

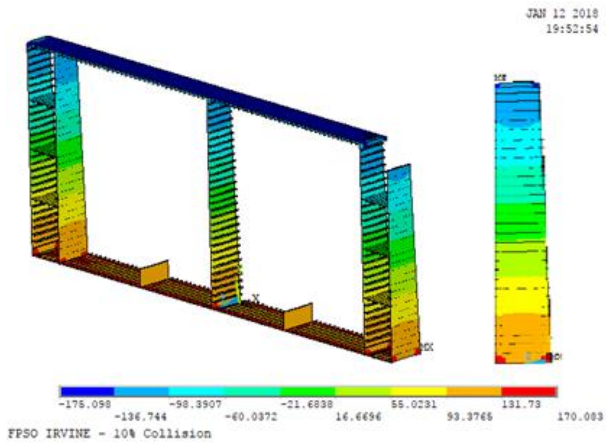


Figure 7. Stress Distribution for 10% Damage Under Sagging Condition

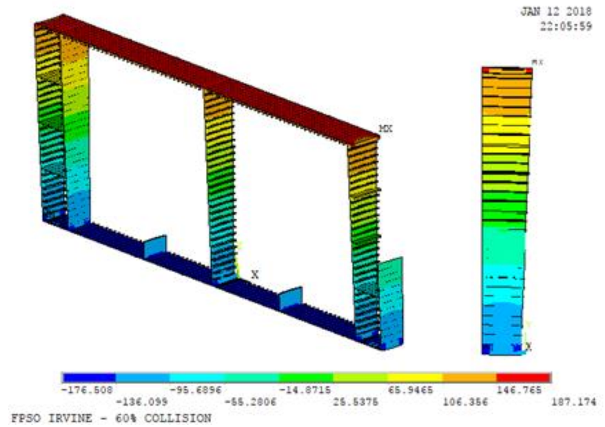


Figure 8. Stress Distribution for 60% Damage Under Hogging Condition

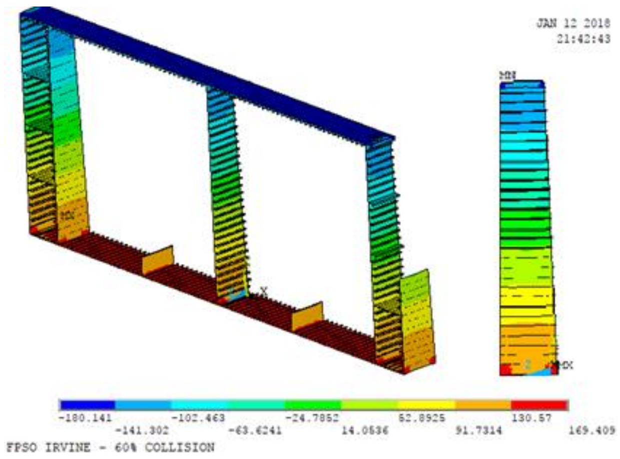


Figure 9. Stress Distribution for 60% Damage Under Sagging Condition

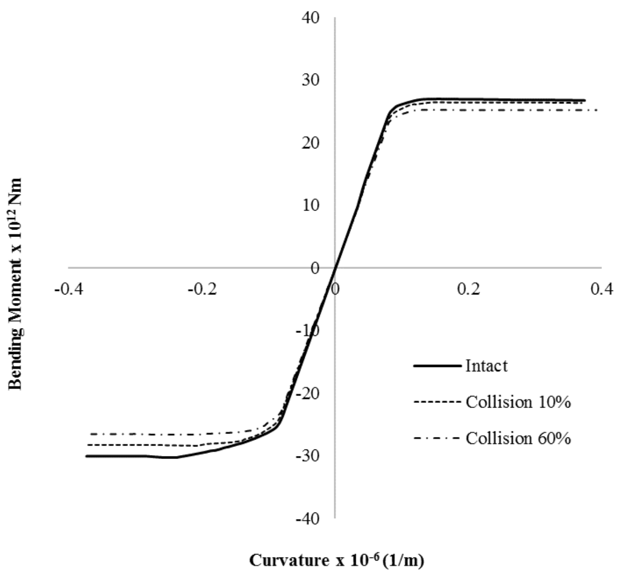


Figure 10. Moment–curvature Relationship

Collisions between FPSO vessels and other ships are possible, and the consequences of such collisions can be severe. The crashworthiness of FPSO side structures must be considered in the preliminary stage of structural design. An analytical method was proposed for rapidly predicting the responses of FPSO side structures to collision with a ship with a rigid bulbous bow. The method is suitable for use in the preliminary phase of structural design because it is based on a series of close-formed formulas derived using a simplified analytical method. Moreover, such analytical method only requires a few parameters for calculation. The proposed analytical method was developed by combining several primary failure models of major double-shell members. Such models include the plate punching model, plate perforating model, plate denting model, plate tearing model, and X-shaped structure crushing model. The curves of impact load versus indentation for three typical collision scenarios were obtained with the proposed method. These curves show in detail the collision process until rupture occurs in the inner shell. They also aid in the evaluation of the crashworthiness of FPSO side structures. The accuracy of the analytical method was verified by numerical simulations using code LS_DYNA [15].

Figure 10 shows the moment–curvature relationship for the cases of intact condition, 10% collision damage, and 60% collision damage under hogging and sagging conditions. The solid line represents the ultimate strength for the intact case. The dashed and dotted lines represent the cases of 10% and 60% collision damage, respectively.

According to the figure, the ultimate strength decreases due to the loss of element stiffness. However, the bending stiffness is a straight line. The significant influence of collision damage is noted under the sagging condition. This result may be due to the elements at the deck and bottom parts showing completely different box-like cross sections.

4. Conclusion

The ultimate strength of FPSO vessels under intact condition, 10% collision damage, and 60% collision damage given hogging and sagging conditions was determined using the proposed numerical solution. The following conclusions can be drawn. The stress distribution spreads from the damaged part to the intact part. The effect of collision damage on the ultimate strength of FPSO vessels is significant due to the loss of element stiffness in the damaged areas.

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