The Study on Assessing the Structural Reliability under the Condition of Ice Loads Against a Floating Body of the Ocean Plant Structure in the Polar Regions

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ABSTRACT

The offshore structures should be able to conduct its proper function even while having varied environmental loads on the sea, and thus, when designing the structure, the various environment loads from the ocean should be considered. The environmental loads should be quantitatively measured over a long period of time, in order to be used as load conditions in the structural analysis, but a lot of time and excessive costs are required for the structural analysis. Therefore, it is necessary that the analysis of structural reliability should be conducted by considering the uncertainty of the environmental loads. In addition, even when manufacturing the offshore structure in shipyard, the uncertainties such as tolerance of the structure should be considered, which occurs frequently in the process of producing and manufacturing the structure.

This paper explains an assessment process of structural safety while considering uncertainties under the condition that the floating structure employed in the polar region under the ice loads. The assessment method of the structural safety will be presented by carrying out the structural reliability analysis for the structure that can reasonably assess the safety of a floating structure. Finally, based on the results derived from the analysis of structural reliability, several guidelines in constructing and operating for the structure will be provided to the field.

INTRODUCTION

The offshore plant structures in the polar region operate under different environment loads such as wave and current impact, strong wind, earthquake, extremely low temperature, ice collision etc. Especially, collision with ice influences to the system of the offshore structure, and eventually it can be broken down if the condition are critical. Therefore, it should be taken into consideration in the design stage.

Carney *et al.* (2006) observed strain rates of the ice and made a failure model. Derradji-Aouat*et al.* (2000) also made a mathematical model for the ice with test data under monotonic and cyclic behaviour of fresh water columnar grained. There are, however, a lot of uncertainties in the collision analysis such as dimension of the structure, the speed and the size as well as material properties of ice of the ice bergy bit.

The uncertainties should be systematically considered in the design stage, since the collision analyses contain difficult statistics information. That is, the results of the collision analysis are dependent on the time, and the maximum points are scattered in many places. Accordingly, the results of the collision analysis should be dealt with statistically. The

structural reliability analysis can be used for taking uncertainties of design variables into account, which should be dealt with systematically and statically. The safety of structure, therefore, can be assessed by probability of failure as considering the uncertainties. The probability failure of the structure can be computed in the design process.
The structural reliability analysis is required in the offshore structure design for estimating safety under collision with ice, because accurate measurement of the loads in the real sea state is extremely difficult. The uncertainties also exist in the manufacturing process as well. The tolerance or material properties of the structures contain significant uncertainties. As the structural uncertainties impact to safety of the offshore plant, the guideline of the structure in the manufacture process is necessary.
To evaluate structural safety of the offshore plant structure, the structural reliability analysis for computing the probability of failure was employed. In this study, limit state equations were obtained from the response surface method (RSM), and the probability of failure was calculated by the Monte-Carlo Simulation (MCS) method. In order to achieve the target probability of failure, design variables with high sensitivity were chosen, and the statistical properties were adjusted to reach the aimed probability of failure. The obtained statistics characteristics can be used as a guideline when the offshore structures are manufactured.

MECHANICAL CHARACTERISTICS AND MATERIAL PROPERTIES OF THE ICE

The mechanical characteristics of ice were estimated as an elasto-plasticity material for collision of ice and offshore structure. Von-Mises yield condition of the structure was applied for the ice as the commercial software, LS-DYNA contained the material model (Halquist, 2007). Nho *et al*. (2016) used change of hardening curve depends on strain rate speed ($\dot{\varepsilon}_t$) and the same curve was considered in this sturdy. The failure condition of the ice was defined failure stain (ε_f) which is the accumulated equivalent statin.
The material properties of the fresh water ice are shown in the Table 1, which were used for the collision test simulation with LS-DYNA. As shown Table 1, three important random variables (RV[1] ~ RV[3])were considered in the material properties. The 10% of covariance (CoV) value was considered for the random variables, and the statistical properties of the random variables were assumed to have a normal distribution.

Table 1. Mechanical characteristics of fresh water ice

M.P.	Mean value	CoV [%]	Probability distributions	No. of Random Value (RV#)
Elastic modulus (E) [MPa]	7800	10	Normal distribution	RV[1]
Density (ρ) [kg/m^3]	970	10	Normal distribution	RV[2]
Yield strength (σ_y)[MPa]	Figure 1.	-	-	-
Failure strain (ε_f)	7.1	10	Normal distribution	RV[3]

COLLISION ANALYSIS MODEL FOR THE OFFSHORE STRUCTURE AND ICE BERGY BIT

Offshore Structure Model for the Collision Analysis

The structural model for the collision test simulation with ice are shown in Figure 1. The structural model for the simulation was modelled with 1/4 symmetric model as the panel structure are symmetric in x- and y- directions. The thickness of the frame was considered as random variables, and the mean values of the thickness are shown in the Figure 2.
Material properties of the structural model was estimated elastic-perfect plastic material, and they are shown in the Table 2. The 10% of covariance (CoV) value was considered for the random variables(RV[4] ~ RV[6]), and the statistical properties of the random variables were assumed to have a normal distribution.
The thickness of the frame are considered as four random variables (RV[7] ~ RV[10]), and the 5% of covariance (CoV) value was considered for the random variables, and the statistical properties of the random variables were assumed to have a normal distribution.

Table 2. Mechanical characteristics of the target structure

M.P.	Mean value	CoV [%]	Probability distributions	No. of Random Value (RV#)
Elastic modulus (E) [MPa]	210000	10	Normal distribution	RV[4]
Density (ρ) [kg/m^3]	7850	10	Normal distribution	RV[5]
Yield strength (σ_y)[MPa]	285	10	Normal distribution	RV[6]

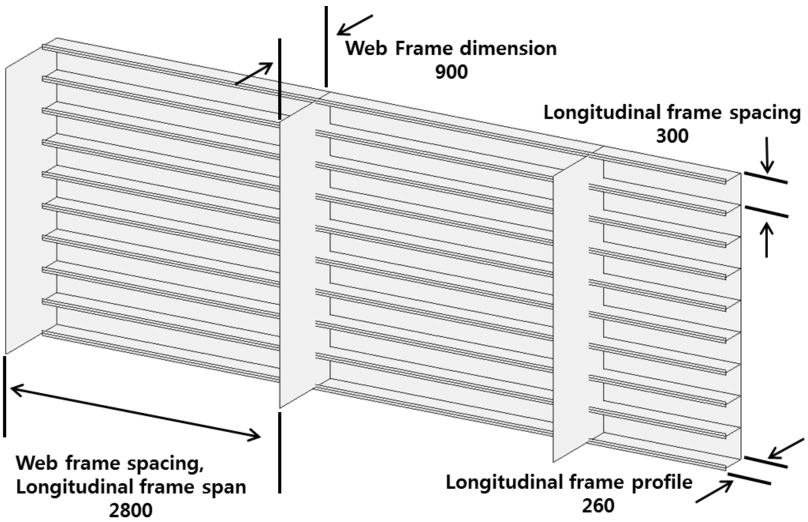


Figure 1. 1/4 symmetric model of offshore panel structure

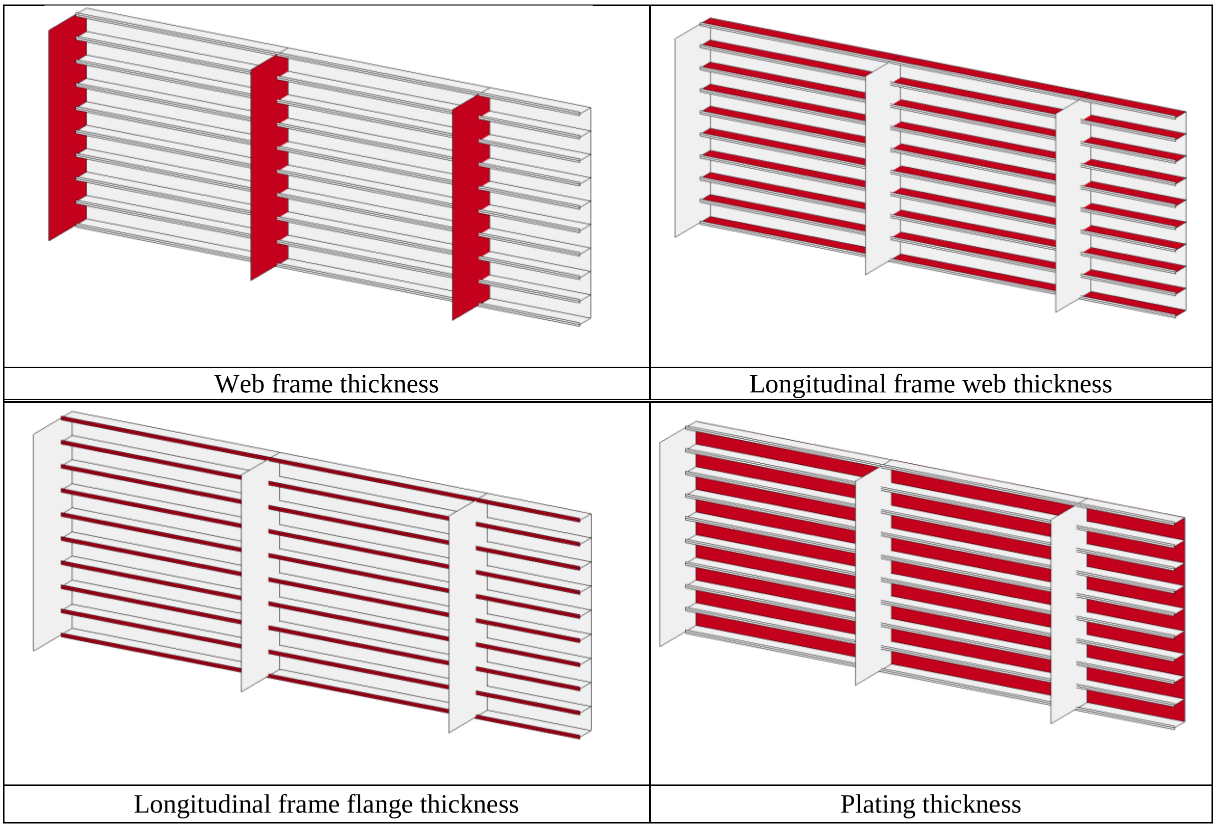


Figure 2. Thickness dimension of the offshore panel structure

Table 3. Dimension of the target structure

Structure member	Dimension (Mean value) [mm]	CoV [%]	Probability distributions	No. of Random Value (RV#)
Web frame thickness	10.0	5	Normal distribution	RV[7]
Longitudinal frame web thickness	10.0	5	Normal distribution	RV[8]
Longitudinal frame flange thickness	27.3	5	Normal distribution	RV[9]
Plate thickness	14.5	5	Normal distribution	RV[10]

Collision Scenario and Modelling for the Ice Bergy Bit

Several cases for the ice collision scenarios were suggested by the class society such as DNV-GL (2006). A typical example case was chosen, in this study, for the collision test simulation between ice bergy bit and structure as shown in Figure 2. There are a lot of things that should be considered for the collision simulation such as collision angle, wave or current speed etc. However, only one case was considered that the sphere ice bergy bit collides to the centre of the structure at 2.0 m/s of speed so that the aims of this study may set up a procedure for the structural reliability analysis. The finite element model of the ice bergy bit is shown in Figure 4, and the size, volume and mass of the ice bergy bit were computed and also shown in Figure 4. Modelling of panel structure and ice bergy bit for the collision test simulation are shown in Figure 5. The 1/4 symmetric model for the panel structure was used and the ice bergy bit collides to the centre of the structure. Simple support condition was applied to the side of the structure, and symmetric condition was applied to the symmetric plane.
The random variables for the structural analysis are shown in Table 4. The diameter and speed of the ice bergy bit is considered as a random variables (RV[11], RV[12]), and the 10% of covariance (CoV) value was considered. The random variables were assumed to have a normal distribution.
In this study, instead of fully coupled hydro-elastic analysis for the collision test, a simple method included added mass of the ice structure for the simulation was considered as Kolari et al. (2009) suggested. That is, added mass of the ice bergy bit was computed (Bishop & Price, 1979), and added on the density of the ice.

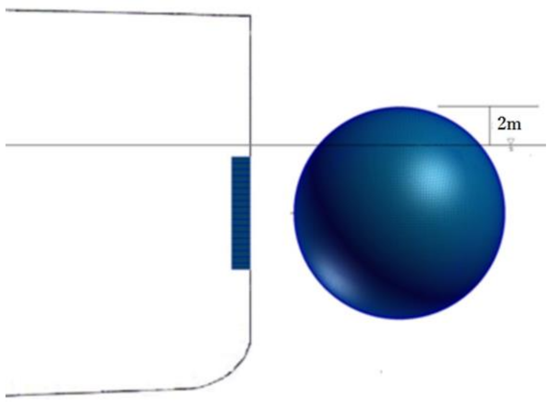
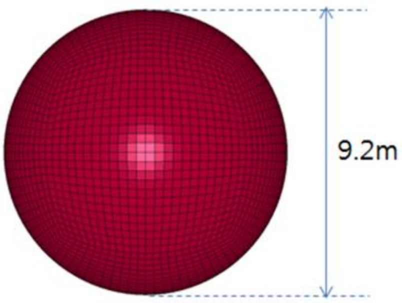


Figure 3. Scenario of ice bergy bit colliding with pannel structure



- Radius: 4.6m
- Volume : 584 m^3
- Mass : 526 ton

Figure 4. FE modelling of spherical ice bergy bit

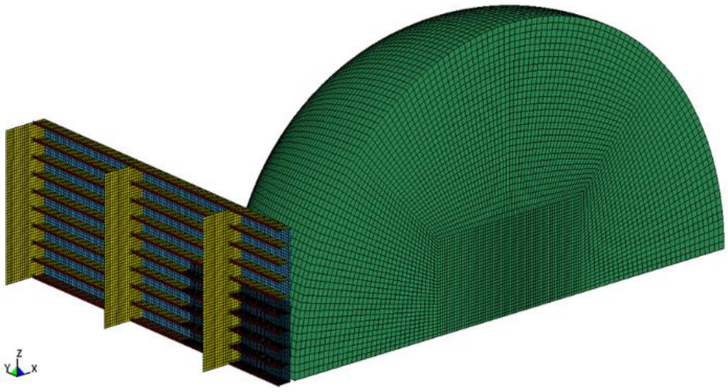


Figure 5. Modelling of panel structure and ice bergy bit

Table 4. Random variables for ice bergy bit

Structure member	Mean value	CoV [%]	Probability distributions	No. of Random Value (RV#)
Diameter [mm]	9200	10	Normal distribution	RV[11]
Velocity [m/s]	2.0	10	Normal distribution	RV[12]

Definition of the Response Value for the RSM Model

The collision results were obtained when all of the random variables are mean values, and ice collision force and effective stress (von-Mises stress) depending on the time were observed as shown in Figure 6 and Figure 7. It is assumed that the failure of the structure occurs when the values of the maximum ice collision force and the maximum effective stress are reaching to the certain figures. Ten of the highest values were selected (round circled values in the Figure 6 and Figure 7), and the averaged values were used for the structural reliability analysis. That is because the values of the maximum ice collision force and the maximum effective stress are changing depends on time. The averaged values were considered as response values for building limit state equation. The limit state equations were obtained by using response surface method (RSM), and probability of failure was computed by using the limit state equations for the two cases, that is, the case for the ice collision force and effective stress (von-Mises stress).

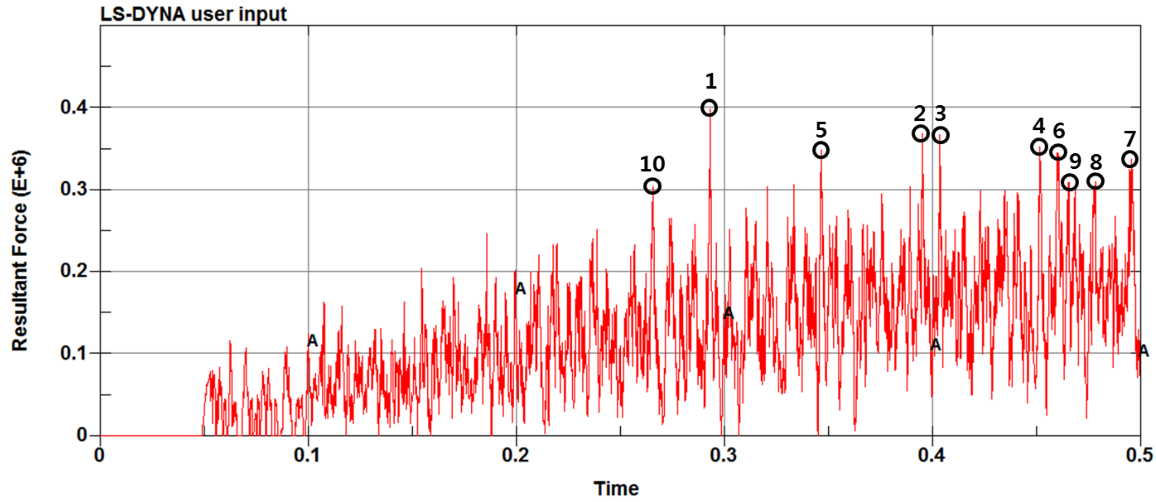


Figure 6. Time history of the collision force

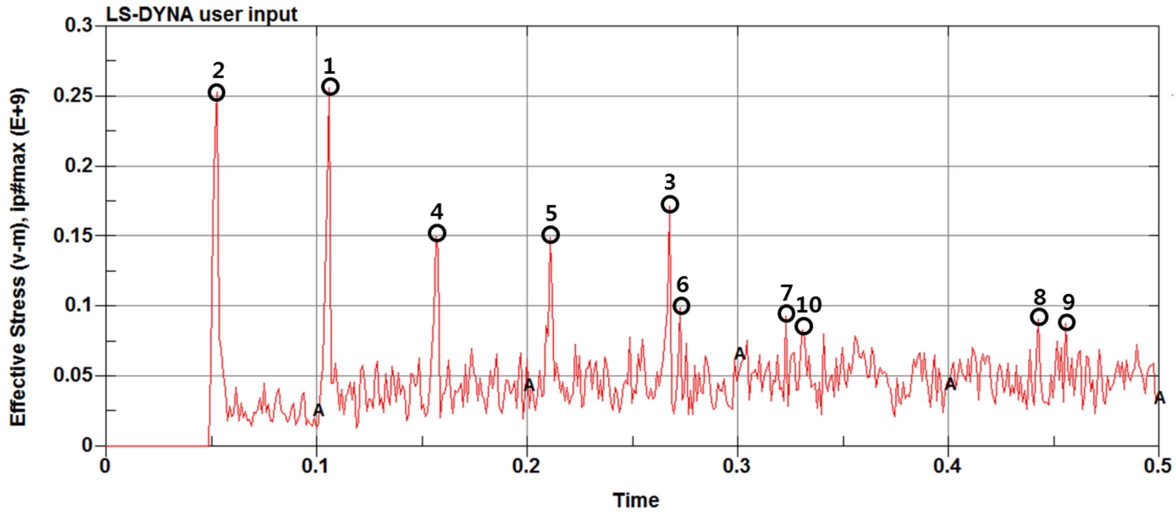


Figure 7. Time history of the effective stress

COMPUTATION FOR THE PROBABILITY FAILURE OF THE STRUCTURE

Limit State Equation and Probability Failure for the Ice Collision Force

Limit state equation was obtained based on the defined 12 random variables in the tables (Table 1～4). The response value for the LSE is the averaged values of the ten points among the highest values of the ice collision force. The total number of sampling points for building up LES is 13 and the probability of failure of the structure was computed based on the obtained LSE by using MCS. The sampling points were selected based on orthogonal array method (Lee, 2013). The obtained LSE based on the computed response value at the sampling points is as follows.

$$\begin{aligned}\text{Collision Force}_{\text{ave}} &= (-370640) + 15.01 \cdot \text{RV1} + 44.31 \cdot \text{RV2} + 3049225.35 \cdot \text{RV3} \\ &+ (-0.411) \cdot \text{RV4} + (-8.643) \cdot \text{RV5} + 2.278 \cdot \text{RV6} + 2264.95 \cdot \text{RV7} \\ &+ (-10935.05) \cdot \text{RV8} + 1690.46 \cdot \text{RV9} + (-6058.65) \cdot \text{RV10} + 54.91 \\ &\cdot \text{RV11} + 191824.75 \cdot \text{RV12}\end{aligned} \tag{1}$$

where $\text{Collision Force}_{\text{ave}}$ represents the averaged values of the ten points among the highest values of the ice collision force, and RV1, .. , RV12 are random variables. The random variables were the same as defined in the tables (Table 1～4).

The probability of failure of the structure was computed based on the above LSE by using MCS. The number of sampling points for computing failure probability is 100,000, and the sampling points were generated by using random numbers generator.

It is assumed that the structure is collapsed or failed when the $\text{Collision Force}_{\text{ave}}$ reaches to the maximum limit collision force 485kN. The computed probability of failure of the structure is about 26.3% as shown in Table 5.

The optimization process was also carried out by setting the target collision force as the objective function, and the allowable collision force as the constraint function. The optimum values that did not exceed the allowable collision force (of 485kN). Sensitivity values for the analysis were also obtained during the analysis process and the results were shown in Table 5.

Table 5. Optimum points and sensitivity values for the limit collision force and probability failure

RVs	***RV1***	***RV2***	***RV3***	***RV4***	***RV5***	***RV6***	***RV7***	***RV8***	***RV9***	***RV10***	***RV11***	***RV12***
Mean value	7800	1380	7.1E-3	210000	7850	285	10	10	27.3	14.5	9200	2.0
Opt. value	8580	1518	7.8E-3	189286	7065	313.5	11	9	30.03	13.05	10120	2.2
Sens. value	0.03	0.008	0.002	0.018	0.01	0.001	3e-5	0.024	0.006	0.017	0.554	0.314
$\mathbf{P}_f$	0.26308											

As obtained sensitivity values shown in Table 5, the most affected components in terms of sensitivity in the LSE were RV[11], RV[12] and RV[1], but others were insignificant for the response value. Therefore, the top three highest sensitive random variable (RV[11], RV[12], RV[1]) were selected for re-computing the failure probability of the structure for reducing the probability of failure.

The covariance (CoV, or standard deviation) of the selected random variables were modified for reducing the probability of failure less than 10%. As shown in Table 6, the CoV of the selected three random variables needed to be less than 6% to fulfil the requirements of the probability of failure, 10%.

Table 6. Probability failure (P_f) observation, with changes of CoV for the collision force

RVs	Mean value	CoV [%] / Standard Deviation					
		10	9	8	7	6	**5**
RV1	7800	780	702	624	546	468	**390**
RV11	9200	920	828	736	644	552	**460**
RV12	2.0	0.2	0.18	0.16	0.14	0.12	**0.10**
$\mathbf{P}_f$		0.26308	0.22121	0.18427	0.14332	0.10397	**0.06479**

Limit State Equation and Probability Failure for the Effective Stress on the Structure

Limit state equation for the effective stress on the structure was obtained by the same way in the previous section. The response value for the LSE is the averaged values of the ten points of the highest values of the effective stress (von-Mises stress) on the structure.
Total number of the sampling points for building up LES is 13 and the failure probability of the structure was computed based on the obtained LSE by using MCS. The obtained LSE based on the computed response value (for the effective stress on the structure) at the sampling points is as follows.

$$\text{Effective Stress}_{\text{ave}} = 147.36 + (-0.01086)\cdot \text{RV1} + 0.02269\cdot \text{RV2} + 573.24\cdot\text{RV3} + (-0.00023)\cdot \text{RV4} + 0.0013\cdot\text{RV5} + (-0.177)\cdot \text{RV6} + (-7.678)\cdot \text{RV7} + (-3.713)\cdot \text{RV8} + 0.412\cdot\text{RV9} + (-17.43)\cdot\text{RV10} + 0.0466\cdot\text{RV11} + 39.385\cdot\text{RV12} \quad (2)$$

where $\text{Effective Stress}_{\text{ave}}$ presents the averaged values of the ten points among the highest values of the effective stress (von-Mises stress) on the structure. and RV1, .. , RV12 are random variables. The random variables were defined in the tables (Table 1～4).

The probability of failure of the structure was computed based on the above LSE by using MCS. The number of sampling points for computing failure probability is 100,000, and it is assumed that the structure is collapsed or failed when the $\text{Effective Stress}_{\text{ave}}$ reaches to the maximum limit effective stress185MPa. The computed failure probability of the structure is about 20.26% as shown in Table 6. The optimum values and sensitivity values for the maximum limit effective stress were also obtained in the analysis process, and the results were shown in Table 6.

Table 7. Optimum points and sensitivity values for the limit collision force and probability failure

RVs	*RV1*	*RV2*	*RV3*	*RV4*	*RV5*	*RV6*	*RV7*	*RV8*	*RV9*	*RV10*	*RV11*	*RV12*
Mean value	**7800**	1380	7.1E-3	210000	7850	285	10	10	27.3	**14.5**	**9200**	2.0
Opt. value	**7262**	1312	0.00641	189000	8635	262	9.79	9.00	30.02	**13.94**	**8377**	2.19
Sens. value	**0.027**	0.002	3e-4	0.007	0.001	0.007	0.018	0.006	0.001	**0.225**	**0.68**	0.026
$\mathbf{P}_f$	0.2026											

The most affected components in terms of sensitivity in the LSE of $\text{Effective Stress}_{\text{ave}}$ were RV[11], RV[10] and RV[1], but other are trivial. The three highest sensitive random variable

(RV[11], RV[10], RV[1]) were selected for re-computing the failure probability of the structure for reducing the probability of failure.

The covariance (CoV, or standard deviation) of the selected random variables were modified for reducing the probability of failure less than 10%. As shown in Table 8, the CoV of the selected three random variables needed to be less than 7% to fulfil the requirements of the probability of failure, 10%.

Table 8. Probability failure (P_f) observation, with changes of CoV for the collision force

RVs	Mean value	CoV [%] / Standard Deviation					
		10	9	8	**7**	6	5
RV1	7800	780	702	624	**546**	468	390
RV10	9200	920	828	736	**644**	552	460
RV11	2.0	0.2	0.18	0.16	**0.14**	0.12	0.10
$\mathbf{P}_f$		0.2026	0.1910	0.1576	**0.1094**	0.0622	0.280

CONCLUSION

Structural safety of the offshore structure was assessed based on the typical collision scenario with an ice bergy bit. The probability of failure was computed by considering uncertainties of material properties and dimensions of the offshore structure and the ice.
The possible 12 random variables were chosen from the design variables of the offshore structure and ice. The structural reliability analysis, then, was carried out based on the random variables, and the probability of failure was computed.
The highest three sensitive random variables were selected for reducing the probability of failure, and the probability of failure was observed modifying standard deviation (or covariance) of the random variables until the failure probability reaches below 10%.
The limit state equations (LES) for the reliability analysis were obtained with the computed response values which were the averaged value of ten points among the highest values of the ice collision force and effective stress on the structure. The two LSEs were obtained and utilized for computing the probability of failure by using the MCS method.
The obtained statistical properties of the random variables of the structure and ice can be used in the design or manufacturing process as a guideline in near future.

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