An Algorithm for the Probabilistic Risk Calculation of Dropped Objects: Application of the Pipeline Protection System of Offshore Platforms

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ABSTRACT

Dropped objects from cranes are one of the most hazardous events during the operation of the topside of offshore plants along with hydrocarbon gas explosion and fire. Although it is strongly suggested by international rules and regulations to evaluate probabilistic impact risk from dropped objects in the offshore industry, most engineers have had difficulties in estimating a reliable risk value because there is no concrete guideline on probabilistic impact risk analysis. Therefore, an algorithm to compute a reasonable probability of structural failure is proposed in this paper. Nonlinear transient finite element structural analyses for a 3D pipeline protection system on a topside module are carried out using LS-DYNA in order to get structural responses for each of the selected dropped object scenarios.

INTRODUCTION

The international standards (ISO 2010) recommend considering the following hazardous events in the design of the topside structures for offshore platforms: 1) explosion; 2) fire; 3) vessel collision; 4) impact from dropped and swinging objects, from projectiles, and from broken cables or wire; 5) helicopter impact (emergency landing or crash); and 6) the effects of accidental flooding due to compartment damage for floating structures, etc. Guidelines on probabilistic risk analysis for each specific hazard, however, haven't yet been established. Given this deficiency, a framework for probabilistic risk analysis of a FPSO (Floating, Production, Storage and Offloading) focusing on impact loads from dropped objects is proposed in this paper.

METHODOLOGY

Drop impact hazard analysis. This section describes the detailed procedure for impact risk assessment, focusing on the event of dropped objects on a topside protection system. In dropped object studies, "*hazard*" is defined as the rate of occurrence of impact energy due to a dropped object such as containers, valves in basket, helifuel, etc. First, all possible dropped object scenarios should be thoroughly investigated for each topside area of a specific offshore platform. Since it is beyond the scope of this study to carry out the complete hazard analysis of dropped objects for a specific FPSO, only two zones shown in Figure 1 are selected in order to give an example of hazard calculation. After choosing a set of dropped object scenarios for each topside area (Zone A and Zone B only in this study), the annual rate of occurrence for each dropped object scenario can be calculated based on the accident database for floating offshore units. The details of dropped object scenarios for the two zones are listed in Table 1.

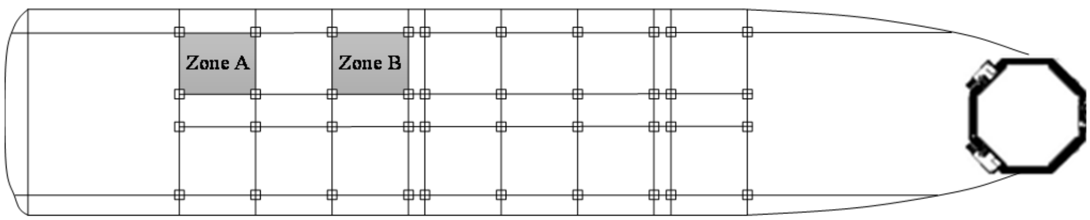
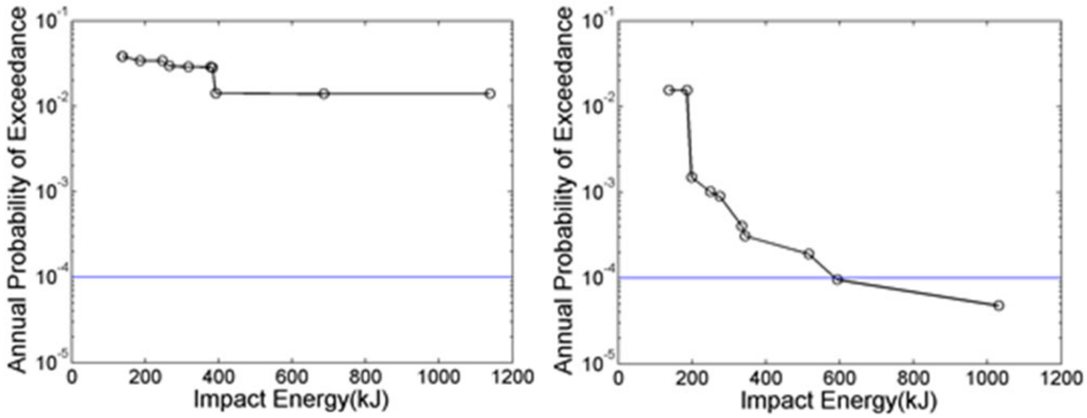


Figure 1. Plan of interesting zones for an example of dropped object analysis.

Table 1. Scenario parameter details for Zone A and Zone B.

Zones	Objects	Weight (kg)	Lift (m)	Impact Energy (kJ)	Dropped frequency (/year)
A	Chemical tanks, empty	2700	1196	384	1.40E-02
	Chemical tanks, full	8000	1196	1139	1.40E-02
	Container	5500	52	378	6.20E-04
	Container	3875	52	266	6.20E-04
	Container	3600	364	247	4.40E-03
	Container	2001	364	138	4.40E-03
	Container to 430	4700	24	392	2.90E-04
	Helifuel	10000	3	687	3.60E-05
	Helifuel	2700	3	186	3.60E-05
	Truck	4625	2	318	2.40E-05
	Valves in basket	2000	2	137	2.40E-05
B	Container	15000	4	1031	4.80E-05
	Container	8625	4	593	4.80E-05
	Container	7500	8	516	9.60E-05
	Container	5000	10	344	1.20E-04
	Container	4875	8	335	9.60E-05
	Container	4000	41	275	4.90E-04
	Container	3625	10	249	1.20E-04
	Container	2900	41	199	4.90E-04
	Empty tote tanks	2700	1196	186	1.40E-02
	Valves in basket	2000	2	137	2.40E-05

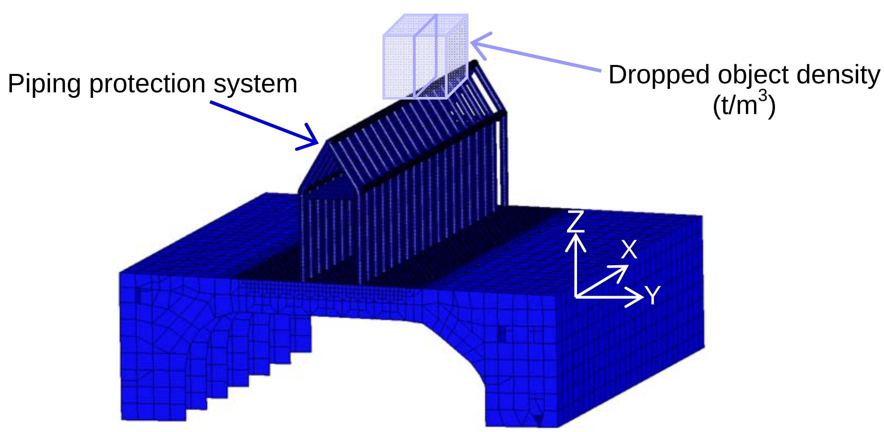
The "*hazard curve*" also called "*exceedance curve*" for each zone is depicted in Figure 2, which plots cumulative summation of the annual rate of occurrence sorted by the impact energy in descending order versus impact energy. Because the entire exceedance curve of Zone A is above the acceptance criteria of 10^{-4} displayed by the horizontal solid blue line in Figure 2(b), it is not necessary to install a piping protection system in Zone A. On the other hand, there is the chance of dropped object load exceeding the acceptance criteria in Zone B. It indicates that a piping protection system is required in Zone B.



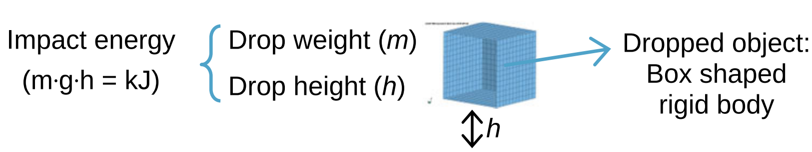
(a) Zone A (b) Zone B

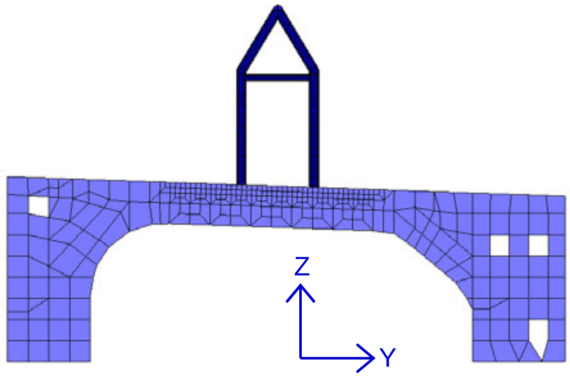
Figure 2. Hazard curves.

Nonlinear transient finite element analysis. After "*hazard analysis*" according to a set of selected dropped object scenarios, a new set of impact load scenarios should be determined for nonlinear dynamic finite element structural analysis. According to the ISO standards (ISO 19901-1, ISO 19901-3, ISO 19902), nonlinear and dynamic effects need to be considered during the structural analysis under accidental loads such as drop impact, vessel collision, explosion, fire, etc. An advanced dynamic finite element simulation software package, LS-DYNA, is used to meet the ISO requirements for structural response in this study. Figure 3 shows the LS-DYNA finite element model.



(a) Iso view





(b) Front elevation view

Figure 3. LS-DYNA finite element model.

Impact load is calculated by the potential energy of the drop object which is converted to kinetic energy when the drop object hits the top center of the piping protection system. In this study, structural analyses were carried out for 11 different cases of impact loads: 49 kJ 245 kJ, 490 kJ, 736 kJ, 981 kJ, 1226 kJ, 1471 kJ, 1717 kJ, 1962 kJ 2207 kJ, and 2452 kJ, varying mass with constant. Although the same impact load is applied to a structure, structural responses can vary due to various parameters such as the impact area on the structure, size of the drop object, drop location, size of the structure (thickness, diameter, etc.), material properties, object stiffness relative to the structure, and boundary conditions.

Limited parameters are considered in this study, as the main purpose of this study is not to improve the accuracy of impact risk assessment but to describe its overall procedure based on the probabilistic approach. In this particular study for a topside protection, the impact area on the protection system varies only when the drop object length in x-direction changes. The following factors are not considered in this study: 1) the effect of drop object deformation; 2) secondary impact due to rebounding; 3) drop location; 4) thickness/diameter of protection pipes; and 5) boundary conditions.

Table 2. Dimensions of drop objects used for eight impact load cases.

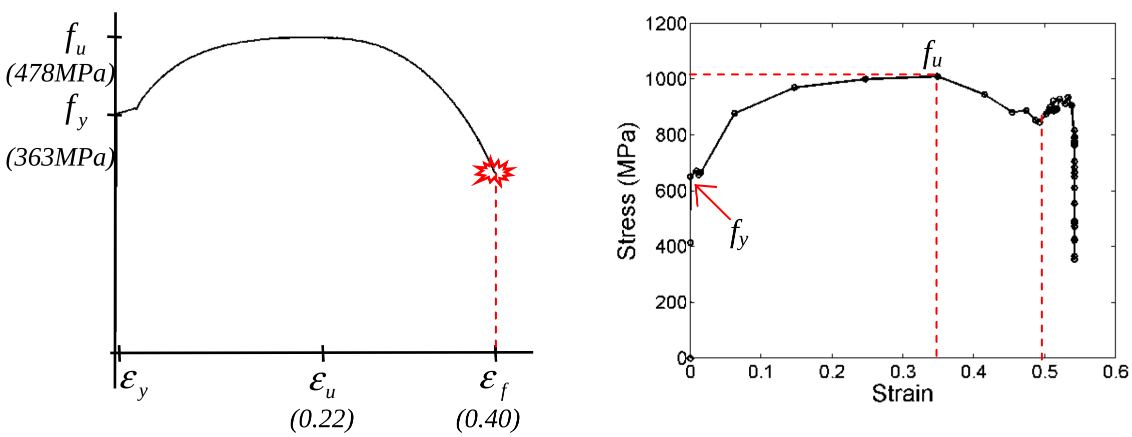
x (m)	y (m)	z (m)	x (m)	y (m)	z (m)
1	1	1	6	2	1
1	1	6	6	2	4
1	4	2	6	6	1
1	4	6	6	6	6

Eight cases of structural analyses listed in Table 2 were additionally performed changing only drop object size along x, y, and z directions for each impact load case so as to roughly see the variation in structural response under the same accidental load in order listed in Table 2.

Figure 4(a) shows the material behavior of the protection system, DH36 steel, during the tension test. It is assumed to fail when the stress falls just below 10% of the ultimate stress (f_u), where the corresponding failure strain (ε_f) is about 30% for DH36 while it is 40% in the experimental simulation. Such material properties, however, significantly change when the strain or stress rate increases or decreases because the steel is a rate dependent material. A strain rate model is incorporated in the LS-DYNA material card adopting Eqn. (1) where f_o denotes the initial yield stress calibrated during the tension test, $\dot{\varepsilon}$ denotes the strain rate, and C and p are the Cowper-Symonds strain rate parameters. The parameters, C and p, are set at 40.4 and 5.0, respectively, in this study.

$$f_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}\right] \cdot f_0 \tag{1}$$

Figure 4(b) shows a sample stress-strain simulation at a finite element on the top of the protection system during the impact loading. Yield stress and ultimate stress are updated to 650 MPa and 1,010 MPa, respectively. Also, strain at ultimate stress (ε_u) changes to 35%, and it is found that if the prescriptive value is 0.3 the failure strain becomes 0.5, much larger than the prescriptive value, for DH-36 steel material.



(a) DH-36 tension test (b) LS-DYNA plastic strain time history

Figure 4. Stress-strain relationship.

During the structural analysis, displacement-based responses such as strain, stress and deformation are produced. These responses, however, cannot represent the structural damage because local failure may sometimes lead to the failure of the entire system but it is also likely that local failure may be negligible depending on the location of the local failure. Therefore, it is necessary to evaluate damage at the system level based on damage at the material level for more precise structural performance. A methodology to reasonably quantify structural damage based on the material damage is proposed by Heo (2009). A simple bilinear model is adopted, assuming that the damage index (D) is 0 until the strain reaches a damage threshold within elastic range in this case and 1.0 when accumulated plastic strain reaches the strain at the residual strength. Structural failure as well as damage state such as mild, moderate and severe damages can be determined by computed damage indices. In this study, it is assumed that the computed maximum plastic strains of the protection system represent the damage.

Table 3. Selected maximum plastic strain and damage index for each impact energy

No	Energy (kJ)	Max. strain	Damage	No	Energy (kJ)	Max. strain	Damage
1	49	0.0219	0.105	50	1472	0.1615	0.806
2	49	0.0229	0.109	71	1962	0.1232	0.614
3	49	0.0233	0.111	72	1962	0.1227	0.611
4	49	0.0241	0.115	73	2207	0.2199	1.000
5	49	0.0050	0.019	74	2207	0.1976	0.988
6	49	0.0050	0.019	75	2207	0.1878	0.939
7	49	0.0049	0.019	76	2207	0.1825	0.912
8	49	0.0049	0.019	77	2207	0.1310	0.653
9	245	0.0722	0.358	78	2207	0.1306	0.651
10	245	0.0743	0.368	79	2207	0.1285	0.640
41	1226	0.1659	0.828	80	2207	0.1288	0.642
42	1226	0.1478	0.737	81	2452	0.2387	1.000
43	1226	0.1477	0.737	82	2452	0.2113	1.000
44	1226	0.1477	0.737	83	2452	0.2017	1.000
45	1226	0.0889	0.442	84	2452	0.1948	0.974
46	1226	0.0888	0.441	85	2452	0.1314	0.655
47	1226	0.0867	0.430	86	2452	0.1313	0.655
48	1226	0.0861	0.427	87	2452	0.1325	0.661
49	1472	0.1771	0.885	88	2452	0.1346	0.671

Based on the selected resulting damage indices in terms of the maximum plastic strain (Table 3), it is observed that the length change along the x-direction is more influential in the computed damages under the same impact energy compared to the y and z directions because the length in x-direction is directly related to impact area on the top of the protection. Although more scenarios for various length especially in x-direction are required to be added, only 88 data are used for regression analysis in this study.

Consequence analysis of the dropped objects. A multi linear regression model for structural response can be established using the computed structural damage values described in the previous section. Impact energy merely counts as the drop impact parameter in this study to exemplify computing the predictive parameters of the regression model as $\ln \overline{D} = c_0 + c_1 \ln E$, where $\overline{D}$ is the expected value of structural damage derived by the maximum plastic strain of the protection system, E is the impact energy, and c_0 and c_1 are the unknown predictive parameters (-5.6464 and 0.7151, respectively). The unknown parameters can be found by applying the actual values of the computed damage and the impact energy for the 88 selected scenarios shown in Table 3 to $\overline{D}$ and E, respectively. Figure 5 displays the actual structural damage computed by the LS-DYNA and the expected values (solid line). The regression model meets quite nicely the trend of the actual structural responses although it is necessary to improve the prediction in order to minimize the scatter in the response by adding more data and examining the other impact load parameters affecting the structural response. A structural fragility curve is created, which provides the exceedance probability of a damage state for the piping protection system at each level of impact energy. Heo (2009) presented details of the methodology of seismic fragility analysis that is adopted in this study.

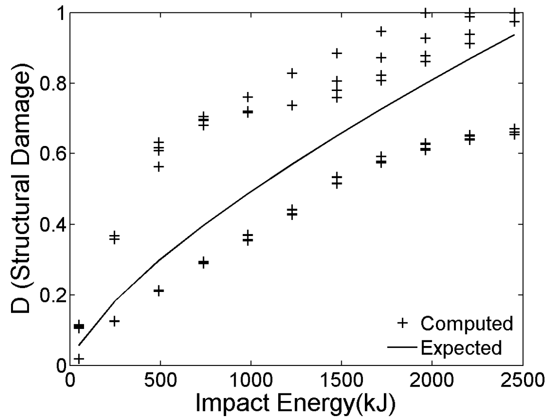


Figure 5. Comparison of the actual structural damage and the expectations.

Drop impact risk calculation. For each drop impact energy range, multiplying the probability of damage state from the fragility curve by the rate of occurrence from the hazard curve gives the marginal rate of the damage state or worse. Summing up the marginal rates returns the risk value for exceeding a specific damage state (Table 4). The resultant risk value can be evaluated by the acceptance criteria determined by mutual agreement among multidisciplinary expert groups of an offshore project or by the request of the owner. Assuming that the acceptance risk level is 10^{-5}, the computed risk values for both cases are not acceptable. Hence, design change to reduce the risk is required in this example.

Table 4. Example of risk calculation.

Impact Energy (kJ)	Rate of Occurrence	Probability of Damage State		Marginal Rate of Damage State	
		40% or worse	60% or worse	40% or worse	60% or worse
100	1.40E-02	0	0	0.00E+00	0.00E+00
200	8.06E-04	0.1	0	8.06E-05	0.00E+00
300	4.21E-04	0.3	0.05	1.26E-04	2.10E-05
400	6.98E-05	0.5	0.2	3.49E-05	1.40E-05
500	1.08E-04	0.7	0.4	7.55E-05	4.32E-05
600	1.10E-05	0.85	0.6	9.32E-06	6.58E-06
700	1.10E-05	0.95	0.75	1.04E-05	8.22E-06
800	1.10E-05	1	0.85	1.10E-05	9.32E-06
900	1.10E-05	1	0.9	1.10E-05	9.86E-06
1000	1.10E-05	1	0.95	1.10E-05	1.04E-05
1100	1.10E-05	1	1	1.10E-05	1.10E-05
>1200	1.40E-02				
			Risk	**3.81E-04**	**1.34E-04**

CONCLUSION

The objective of this paper is to establish an explicit procedure for risk assessment through a sample study using a topside protection system subjected to drop impact loading. The procedure is summarized in the foregoing sections. In order to work out reasonable and precise risk, further studies are needed: First, offshore accident database should be reliable. Secondly, structural response estimation should be sufficiently accurate considering nonlinear and dynamic effect, which is the basis for the decision on the expected damage state. Moreover, predictive parameters for the structural response regression model and load intensity regression model should be investigated. The proposed approach, however, is versatile as it can be applied to different risk assessments for other accidental events on any type of structure.

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