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Risk-Identification-Based Hybrid Method for Estimating the System Reliability of Existing Jacket Platforms Under Fire

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Abstract: This paper proposes a risk-identification-based hybrid method for estimating the system reliability of steel jacket structures under fire. The proposed method starts with risk identification; according to the results of hazard identification and Dow's fire and explosion index (F&EI) methodology, the most dangerous hazard sources are determined. In term of each equipment layout in steel jacket structures, fire load is imposed and elasto-plastic analysis is performed. According to the deformed state of steel jacket structures, the weakest failure mode of steel jacket structures is identified. In order to know the effect on ultimate bearing capacity of the offshore structural system, a series of elasto-plastic analyses are performed in which single failure element contained in the weakest failure mode is removed from the whole offshore platform structural system. Finally, the failure function of the steel jacket structure is generated and the failure probability of the steel jacket structure system is estimated under fire by genetic algorithm via MATLAB program.

Key words: hazard identification (HAZID), steel jacket structure, relative importance factor, failure probability, genetic algorithm (GA)
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0 Introduction

In the offshore oil exploitation activities, steel jacket structures have been extensively employed. There are more than 5 000 types of jacket platforms in the world. Besides the normal operational loads, the platforms are usually subjected to other loads, such as fire, explosion and wave. In the case of steel jacket structures under fire, fire causes structural failure mainly by reduced strength due to heating, but to some extent, also due to thermal stresses. Therefore, the system reliability analysis of jacket platforms under fire has become important topics for risk-based assessment of steel jacket structures.

Great progress has been made in recent years on estimating the reliability of structure systems under uncertain loads. However, since practical steel jacket structures are usually indeterminate and have many possible failure modes, one of the key issues is to identify the dominant failure modes effectively. In the recent two decades, many studies have been carried out by scholars and some algorithms have been proposed. Li et al.[1] proposed a reliability method for assessing the stabilities of rock wedges by considering many correlated failure modes. Using the N-dimensional equivalent method, a system reliability analysis was performed. Abou[2] adopted a lot of alternative measures of multi-state structural systems which contained two failure modes, and proposed a technique for assessing these measures. Neves et al.[3] proposed a local approach of reliability analysis applied to grid structures by considering the main failure modes. This method used random sampling combined with finite element analysis, and used a localized response surface technique. Park et al.[4] proposed a reliability assessment method by directly assessing the reliability of a complex structural system using the reliabilities of its components or elements. Gharaibeh et al.[5] proposed a method by identifying and ranking the important components of structural systems for different material behaviors and different stiffness sharing factors. The results can be used to form a rational method in order to perform the prediction of critical members of structural systems. Shao and Murotsu[6] proposed a selective search technique coupled with the genetic algorithm (GA), and obtained more robust methods for production of failure modes. Qin et al.[7] proved that the failure mode obtained by the elasto-plastic analysis

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using finite element analysis was the same as the weakest failure mode obtained by the extensive searches or simulations. The property of hazard loads was studied in Refs. [8-9] by introducing the load roughness index, and conclusions were as follows: the structural failure modes under hazard loads were fully correlated and the structural system reliability under hazard loads could be estimated by the failure probability of the weakest failure mode. The hazard category of a process plant, the area of exposure, the expected losses in case of fire and explosion and so on were evaluated in Refs. [10-11] by using the Dow's fire and explosion index (F&EI). Khan et al.[12] described a method for the risk-based process safety decision making for an offshore oil and gas (OOG) activities. The method applied to various offshore process units, such as compressor, separators, flash drum and driers of OOG platform.

Although previous study has made great progress in the structural reliability, a number of problems remain unresolved. This paper proposes a risk-identification-based hybrid method for evaluating the steel jacket structures under fire. Firstly, the potential hazard sources and risk level are determined by using the hazard identification (HAZID) method[12] and the F&EI method[10-11]. The F&EI method is denoted as the Dow's method. Secondly, according to the proposed method, the system reliability analysis of steel jacket structures is performed. Finally, failure probability and reliability index of are obtained.

1 HAZID and Fire-Explosion Index Method

HAZID is a research process that performs hazard identification and classification by considering accident causes, locations, frequency, consequences, operation type and other factors. HAZID analysis process is shown in Fig. 1.

Based on the previous incident statistical information, i.e. the potential matter energy and the existing safety measures, using technological process, equipment, material quantity and other data, Dow's method can be used to evaluate system craft device, actual potential fire and explosion risk and reactive risk. Dow index evaluation process is shown in Fig. 2. Fire explosion index risk levels are shown in Table 1.

Table 1 Fire explosion index risk levels

F&EI	Risk level
1—60	Lightest
61—96	lighter
97—127	Middle
128—158	Severe
> 159	Severer

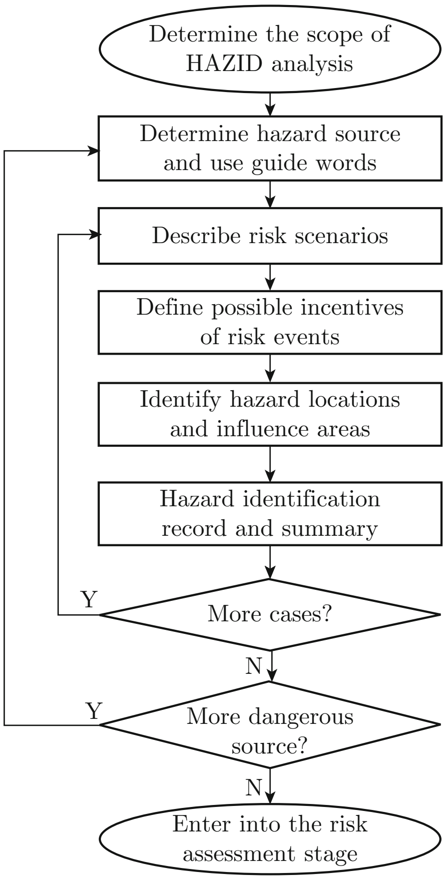


Fig. 1 Work flow of HAZID analysis

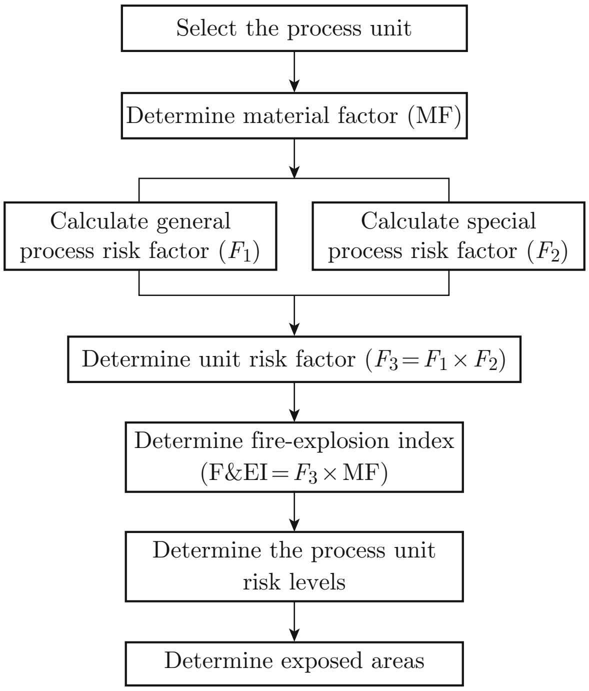


Fig. 2 Dow analysis work flow

2 Approximate Calculation of Structural System Reliability Under Disaster Load

Structural loads can be divided into non-disaster loads and disaster loads: non-hazard loads include dead load, live load, wind load, snow load and the role of frequent earthquake; disaster loads include fire, explosion, hurricane, rare earthquake, catastrophic flood and so on. Severe structural damage or collapse will occur under disaster loads. These will cause great loss of life and property. Therefore, it is very important for estimating the health of overall performance of the structure.

The property of hazard loads was studied in Refs. [8-9] by introducing a load roughness index; the correlation between structural failure modes and the approximate calculation of structural system reliability under hazard loads were proposed.

The structural failure modes under disaster loads are fully correlated and the structural system reliability under disaster loads can be determined by the weakest failure mode, i.e. the failure mode with maximum failure probability has commonly occurred before failure modes with lower failure probabilities occur. In the main failure modes of a structural system, the weakest failure mode is defined as the failure mode with the maximum failure probability.

If E_i is the event that failure mode i occurs, then the probability of failure of the structural system can be expressed by

$$P_{\text{system}} = P\left(\bigcup_{i=1}^{N} E_i\right), \tag{1}$$

where N is the number of possible failure modes.

Because perfect correlation between any two failure modes has been assumed, it follows that

$$P_{\text{system}} = \max\{P_1, P_2, \cdots, P_N\}, \tag{2}$$

where P_i is the probability of occurrence of the event E_i.

According to Ref. [13], the probability of occurrence of the event E_i under disaster loads can be expressed by

$$\begin{aligned} &P(E_i) \approx \min_{k_i=1,2,\cdots,n_i} P(e_{k_i}), \qquad (3)\\ &\{e_{k_i}\} = E_i, \end{aligned}$$

where n_i is the number of failure elements of the event E_i.

According to Eqs. (2) and (3), the failure probability of structure system under disaster loads can be expressed by

$$P_{\text{fdl}} \approx \max_{i=1,2,\cdots,N}\left(\min_{k_i=1,2,\cdots,n_i} P(e_{k_i})\right). \tag{4}$$

3 Genetic Algorithm for Reliability Analysis

In recent years, first-order reliability method (FORM), second-order reliability method (SORM) and Monte-Carlo simulation (MCS) method are widely used in the structural reliability analysis. These methods need to evaluate the evolution of limit state function about the random variables. In addition, a main disadvantage of these methods may lead to erroneous results when the limit state function has a number of local minimum distance points. GA has also been widely used in reliability analysis[13]. Compared with FORM or SORM, GA has the advantages that it does not involve the difficulty of calculation of the evolution of limit state function about random variables, and it can recognize the global optimum values of limit state function.

As for the GA application in reliability analysis, a clear expression is made by

$$\min\ \beta = \|\boldsymbol{\mu}\|^2 = \boldsymbol{\mu}^{\mathrm{T}}\boldsymbol{\mu}, \tag{5}$$

$$\text{s.t. } g(\boldsymbol{\mu}) = 0, \tag{6}$$

where $\boldsymbol{\mu}$ is a vector of standard normal variables, β is the reliability index, and $g(\boldsymbol{\mu})$ is the limit state function. In this paper, GA is used to solve the optimization problem.

4 Proposed Risk-Identification-Based Hybrid Method

Under the action of fire, the procedure of reliability analysis of existing platform structural system is used as follows.

(1) Using the HAZID method, the potential hazard sources are identified.

(2) Using the Dow's method, the loss caused by fire is forecasted, the explosion and reactivity accident is truly quantified, and the equipments that may cause the accident occurrence or potential fire and the explosion risk levels are also determined.

(3) Using the results of Steps (1) and (2), the most likely occurrence locations of fire are determined.

(4) According to the results of Step (3), the fire load is imposed, then the elasto-plastic analysis is performed using finite element software ANSYS, and the weakest failure mode is obtained.

(5) The failure elements are removed in turn from the weakest failure mode of jacket platform, and then a series of post-failure behavior analyses are performed to assess the relative importance of different components in the weakest failure mode. Relative importance factor[7] is defined by using the ratio of the ultimate bearing capacity of damaged structure to that of the intact structure.

(6) By Step (5), the member with the maximum relative importance factor is obtained. According to

Ref. [7], the component is regarded as an equivalent system of jacket platform.

(7) Using finite element software ANSYS, the safety margin equation of the component with the biggest relative importance factor is obtained, and then using GA via MATLAB, the reliability index and the failure probability of jacket platform are obtained.

5 Application of the Proposed Method in Offshore Platform

In the case of the jacket platform system locating in complex marine environment, there are two main uncertainty factors that affect the reliability of structure: the approximate of the mechanical model from calculation analysis, and the random of material mechanical properties which include the variation of geometry size of structure, load distribution and so on.

Therefore, reliability analysis of the damaged platform structural system can be attributed to the following limit state equation[14]:

$$Z = B_{\mathrm{r}}R - B_{\mathrm{l}}Q, \tag{7}$$

where, R is the resistance of platform structure system; Q is the effect of total load; B_{r} and B_{l} are the deviation factors of resistance and load effect calculation model, respectively. Deviation factor B_{r} of the system resistance model is determined by the ratio of finite element analysis and test results. According to Ref. [14], B_{r} obeys log-normal distribution, $\ln N(1.034, 0.086)$, and B_{l} obeys normal distribution, $N(1.060, 0.265)$.

5.1 Case Study Offshore Platform Description

A jacket platform is used as a case study to illustrate the process for estimating the reliability of structure due to uncertainty factors. It locates in the western of South China Sea. The jacket central platform has 8 legs, 16 well slots and 17 production wells. Natural gas of 1 533.6 m^3 (standard state) is produced every year. In addition, the platform consists of upper, middle and lower decks.

The structural model of jacket platform is established by general finite element software ANSYS; the model, presented in Fig. 3, is rather complex. Yielding tension and elastic modulus of the material are 0.355 and 206 GPa, respectively. The structure model contains 7 620 elements and 6 950 nodes. Since an actual offshore jacket structure is very complex, detailed information regarding section properties for each element will not be presented here. The value of dead weight and vertical deck loads acting on the structure is 117 MN.

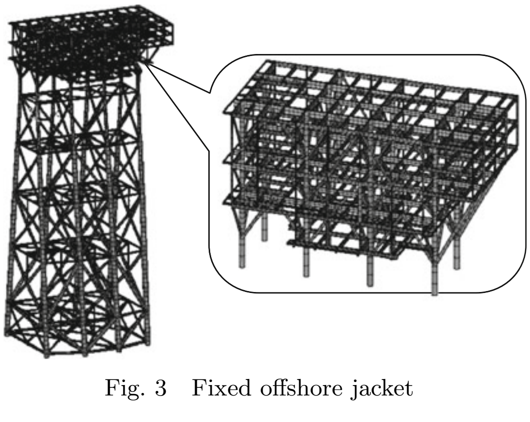


Fig. 3 Fixed offshore jacket

5.2 System Reliability Analysis of the Jacket Platform Structural Under Fire

According to the HAZID and Dow's method, fire and explosion hazard index calculation results are shown in Table 2.

As seen in Table 2, due to the complicated gas field process and higher process pressure, important production facilities on the platform, such as production separator and compressor, have higher inherent risk. Especially for the unit facilities with high pressure and high-flow gas process, inherent risks are quite obvious. The results of Table 2 are unit risk conditions that don't take any security measures. In fact, before the existing offshore platforms are built, many necessary security measures have been taken. Therefore, this paper selects two most serious conditions as the load combination condition studying the existing jacket offshore platform. That is natural gas filter and gas cooler contact tower in Table 2. In term of each equipment layout in the platform structural system, the fire load locations imposed are determined.

Because the structural systems of offshore platform have very high redundancy and contain many failure modes with complicated correlation among them, the disaster load is considered as the control load[8-9]. When the correlation of structural failure modes is considered, other non-hazard loads can be ignored and the single load (hazard load) is considered.

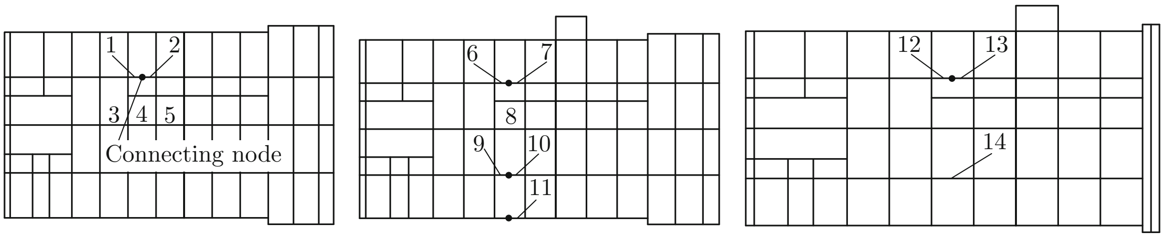
The elastic-plastic analysis is performed to gain the weakest failure mode and ultimate bearing capacity of the undamaged jacket platform. Because the substructure deformation of the jacket platform structural system is very small and can be ignored, we only select the deformation of upper structure, as shown in Figs. 4 and 5.

As seen in Fig. 4, when fire occurs, though the load acting on the jacket platform doesn't change, elastic modulus and yield strength of the material under fire decrease with the increase of temperature, while the

Fig. 4 The weakest failure mode of the jacket platform under fire

Table 2 Fire and explosion hazard index and risk level

Device	MF	F_1	F_2	F_3	F&EI	Risk level
High pressure measurement manifold	21	1.55	3.01	4.67	97.98	Middle
High pressure production manifold	21	1.55	4.04	6.26	131.50	Serious
Low-pressure measurement manifold	21	1.55	2.71	4.20	88.21	Lighter
Low-pressure production manifold	21	1.55	3.82	5.92	124.34	Middle
High pressure measurement separator	21	1.55	3.24	5.02	105.46	Middle
High pressure production separator	21	1.55	3.81	5.91	124.02	Middle
Low pressure measurement separator	21	1.55	3.32	5.15	108.07	Middle
Low pressure production separator	21	1.55	4.14	6.42	134.76	Serious
High pressure natural gas cooler	21	1.55	4.11	6.37	133.78	Serious
Low pressure natural gas cooler	21	1.55	2.49	3.86	81.05	Lighter
Subsea wellhead plug flow catcher	21	1.55	4.24	6.57	138.01	Serious
Condensate oil aggregation separator	16	1.55	2.98	4.62	73.90	Lighter
Condensate oil output pump	16	1.55	3.15	4.88	78.12	Lighter
Compressor enter gas polyester device	21	1.55	4.69	7.27	152.66	Serious
Natural gas compressor sled	21	1.55	4.78	7.41	155.59	Serious
One-level compressor post cooler	21	1.55	4.61	7.15	150.06	Serious
One-level air polyester apparatus	21	1.55	4.62	7.16	150.38	Serious
Two-level compressor post cooler	21	1.55	4.83	7.49	157.22	Serious
Two-level air polyester apparatus	21	1.55	4.84	7.50	157.54	Serious
Natural gas filter	21	1.55	5.09	7.89	165.68	Special serious
Gas cooler contact tower	21	1.55	5.03	7.80	163.73	Special serious



(a) Upper deck (b) Middle deck (c) Lower deck

Fig. 5 Component distribution diagram of the most weak failure mode

carrying capacity of the jacket platform decreases, too. When the temperature rises to some extent, a sufficient number of plastic hinges are formed and a limit state of the jacket platform arrives, finally damage or collapse of the jacket platform is caused.

According to the proposed method, firstly, the relative importance of the failure components contained in the weakest failure mode is evaluated. In this study, the relative importance factor is defined by the rate of the ultimate bearing capacity damaged versus the ultimate bearing capacity undamaged, the failure elements are removed in turn from the weakest failure mode of jacket platform, and then a series of post-failure behavior analyses are performed to assess the relative importance of different components in the weakest failure mode. The member with the maximum relative importance factor of 0.999 is obtained. According to Ref. [14], the component is regarded as an equivalent system of the jacket platform. According to the component numbers shown in Fig. 5, the detailed information is listed in Table 3.

Table 3 Relative important factors in the weakest failure mode

Component	Factor	Component	Factor
IJPS	1.000	8	0.996
1	0.994	9	0.974
2	0.989	10	0.981
3	0.988	11	0.976
4	0.999	12	0.999
5	0.984	13	0.999
6	0.983	14	0.999
7	0.978		

Note: IJPS—Intact jacket platform structure

According to Eqs. (4) and (6), safety margin equation of the equivalent system of jacket platform is obtained as

$$Z = 8\,511\,480B_{\mathrm{r}} - 48\,310B_{\mathrm{l}}.$$

By using GA via MATLAB, the failure probability of jacket platform is 2.83×10^{-4}. Tracking map of optimization performance of GA is shown in Fig. 6.

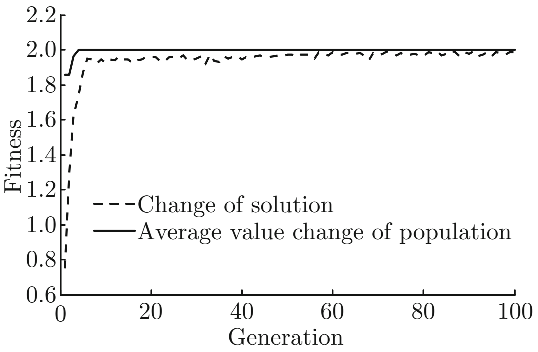


Fig. 6 Tracking map of optimization performance of GA

6 Conclusion

A risk-identification-based technique is proposed for the system reliability estimation of the existing offshore structural system under fire. The method is implemented by combining with the general-purpose finite element software ANSYS.

Using the HAZID and Dow's method, potentially dangerous source can be identified, and can be provided for maintenance, inspection and design. Some protective measures can be taken to prevent accident occurrence.

According to the relative important assessment, some members should be emphatically inspected and reinforced when design and maintenance of the offshore structure are performed.

When other non-hazard loads can be ignored and the single load (fire load) is considered, the failure probability of offshore structure is about 10^{-4} order of magnitude under fire.

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