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RELIABILITY OF SUBSEA PIPELINES

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ABSTRACT

The subsea industry is having to face increasingly more challenges to develop hydrocarbon reserves in the marginal and more in accessible fields around the world. These challenges include those associated with deep water, high pressure/ high temperature, aggressive environments and economic restrictions. All of these put increasing demand on the achievement and improvement of reliability at every stage of the system life cycle. The reliability depends strictly on the design rules and the associated parameters that have been used in system design. So the evaluation of reliability requires an understanding of design methodologies and what design parameters can cause and increase unreliability in a designed system. This study provides a comparison of DNV and API Design Methodologies for Subsea Pipelines and discusses the rules and parameters for designing subsea pipeline by each method. Reliability of both DNV and API designed subsea system is evaluated using corresponding Limit State Equations. The results that have been achieved are applied to a realistic model and suggestions are made for a more reliable method.

KEYWORDS: Subsea Pipeline – System Reliability – Failure Modes

INTRODUCTION

This paper is concerned with the application of design standards for subsea pipelines. The subsea pipelines have been constructed for different purposes such as transformation of crude oil and gas transmission. Some countries use their own standards as guideline for design of subsea pipeline. In our country, Iran, the most popular used standards are API rule and DNV design standards which will be compared in this paper.

There are many discussions which standard is the best one. The main differences in subsea pipeline standards are in the classification of safe zone, the differences in safety factor definition which depends on the material, wall thickness, diameter, environment, loads, and pipe manufacturing procedures.

On the other hand, in structural analysis and safety calculation, the designer is solely concentrated on the behavior of individual elements and the safety factors (in Working Stress Method) or Load factor (in Limit State Method) are controlled. In structural system reliability, the structure involves a variety of structural elements and the elements are used to form a "system" concept and not the individual elements alone.

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Occasionally, the failure of an element may weaken the system of whole structure (progressive collapse), other elements will undergo the failed element function and finally the system failure will pass with alternative path. For this reason, the structural reliability of a structure will yield to system reliability analysis problem.

Two special series system and parallel system have important effects in structural reliability. In series system, the elements have arranged

ANALYTICAL MODELS OF RELIABILITY ANALYSIS

In mathematical sense, the determination of the probability of failure comes down to calculating an n-fold integral, n being the number of basic variables. In integration of the limit state function requires the probability knowledge for the resistance and load parameters and also by application of modern computers, it is found that the integration of this differential equation consumes a lot of *CPU* time even for the simple engineering problems. However there are two convenient approximate methods for the evaluation of this integral which are called the *transformation methods* and the *simulation methods*. In the transformation method, the original integral is transformed to the integral in boundary of independent standard normally distributed variables. The first transformation is used for the transformation of correlated basic variables to uncorrelated variables that often requires the determination of *Jacobian* matrix. The second transformation is usually carried out by the *Rosenblatt* transformation that is used to find the independent standard normal varieties from the initial probability density functions (note that they are not necessarily normally distributed). By this formulation, the safety index can be evaluated by the so-called *Hohenbichler* algorithm.

The transformation methods are often split to *FORM* and *SORM* methods. In the next section, we will discuss the linear transformation methods (or a so-called *FORM* procedure). It should be emphasized that the use of *FORM*/*SORM* methods does require some caution, insight and experience in reliability computation. Among the Level II reliability methods, in the mean-value first order second-moment method (MVFOSM) method the linearization of the limit state function takes place at the mean value (MV). The method is formulated on the basis of linear approximation of failure surface and only the first order terms are retained in Taylor series expansion. For application of MVFOSM method, the non-normal distributions of the variables should be converted to equivalent normal distributions.

However, for non-linear safety margins, an equivalent and approximate failure function has to be defined by linearization of the safety margin function. The advanced first order second-moment method (AFOSM) has been introduced by Hasofer and Lind (1974) and this approach is implemented by expanding the safety margin in a Taylor series about the linearization point. Such as the MVFOSM method, the point which corresponds to the shortest distance from equivalent linear failure surface is referred to as design point or checking point and the distance β (safety index or the corresponding failure probability) can be determined by an iterative procedure [1].

If the limit state function is defined by *n* uncorrelated random variables, the linearized safety by Taylor series is expanded at point X^0 as follows:

$$M = M^0 + \sum_{i=1}^{m} (x_i - x_i^0) \frac{\delta M_i^0}{\delta x_i}$$

In which $M^0 = M(x_1^0, x_2^0, ..., x_n^0)$ is the value of the function *M* at design point $X^0 = (x_1^0, x_2^0, ..., x_n^0)$ and the

SYSTEM RELIABILITY

In approximation of limit state functions to uncorrelated standard normalized variables, the first order derivative of Taylor expansion is used for the computation of failure probability of series system [2]:

$$p_{f,sys} = p[\bigcup_{i=1}^{n}(M_i \le 0)$$

$$= p[\bigcup_{i=1}^{n}(\beta_i - \alpha_i^T u \le 0)]$$

$$= 1 - p[\bigcap_{i=1}^{n}(\alpha_i^T u \le \beta_i)]$$

$$= 1 - \phi_n(\beta, R)$$

In which $\beta = [\beta_1, \beta_2, ..., \beta_n]^T$ are the vector of safety indices and $R = [\rho_{ij}] = [\alpha_i^T \alpha]$ is the correlation matrix between safety margins.

PIPELINE INTERNAL PRESSURE LIMIT CALCULATION METHODS

In this study it was used 2 main API and DNV different standards for simple design pressure calculations based on wall thickness, diameter and yield stress for thin pipes.

It is quite complicated to analyze generally these standards, because the equations are based on the hoop stress and safety factors that are related with many other factors and best practices [3].

In both of these norms design pressure in pipes is based on:

- Wall thickness,
- Diameter,
- Specified minimum yield strength,

Safety factors based on

- Material characteristics,
- Environment,
- Loads,
- Temperature,
- Type of pipe manufactory,
- Other integrated correction factor.

INTERNAL PRESSURE DESIGN – DNV-OS-F101, 2000 [4]

The limit state function for pressure containment $p_{dy,}$ (t) and $p_{dy,}$ (t) is given by minimum of equations (5.15) and (5.16) in section D403, DNV rule:

$$p_d(t) = Min(p_{b,y}(t), p_{b,u}(t))$$

Yielding limit state:

$$p_{b,y}(t) = F\frac{2t(\sigma_y - f_{y,temp})}{(D-t)}, \qquad F = \frac{2}{\sqrt{3}}\frac{a_u}{\gamma_m \gamma_{sc} \gamma_{inc}}$$

Bursting limit state:

$$p_{b,u}(t) = F\frac{2t[(\sigma_u - f_{u,temp})/1.15]}{(D-t)}, \qquad F = \frac{2}{\sqrt{3}}\frac{a_u}{\gamma_m \gamma_{sc} \gamma_{inc}}$$

For the material characteristics of API-X65, the pressure containment based on yielding $p_{b,y}$ (t) governs and in the rest of this paper the second formula for bursting limit state $p_{dy,}$ (t) is omitted.

The limit state function is formulated by rearranging the pressure containment based on yielding $p_{b,y}$ (t) as follows:

$$g_{DNV}(X) = t[2F(\sigma - f_{y,temp}) + p_{b,y}] - p_{b,y}.D$$

Where g(X) is the limit state function based on the deterministic and random variables given in the vector form (X).

INTERNAL PRESSURE DESIGN – API RP1111, 1999 [5]

The wall thickness is calculated based on the specified minimum burst pressure, design pressure and hydrostatic test pressure:

$$p_d(t) = Min(p_{d1}(t), p_{d2}(t))$$

The first equation for $p_{d1}(t)$ is given by:

$$p_{d1}(t) = F.0.45(S+U)\ln(\frac{D}{D-2t}), \qquad F = 0.8 f_d f_e f_t$$

$$p_{d2}(t) = F.0.9(S+U)(\frac{t}{D-t}), \qquad F = 0.8 f_d f_e f_t$$

Where:

D: Outside diameter of pipe,
S: Specified Minimum Yield Strength (SMYS) of pipe (See API specification 5L, ASME B31.4, or ASME B31.8 as appropriate),
t: Nominal wall thickness of pipe,
U: Specified Minimum Ultimate Tensile Strength (SMTS) of pipe,
f_d: Design factor,
f_e: Longitudinal Weld Joint Factor,
f_t: Temperature De-rating factor,
ln: Natural logarithm,

For the material characteristics of API-X65, the pressure containment based on the first equation governs and therefore only this equation is adopted for further study.

By rearrangement of the first equation, the limit state function is formulated as follows:

$$g_{API}(X) = 0.8 f_d\ f_e\ f_t.0.45.(S+U).\ln(\frac{D}{D-2t}) - p_d$$

NUMERICAL ANALYSIS

As mentioned earlier, the First Order Reliability Method (FORM) is one of the significant computational methods for both element reliability and system reliability analysis. According to common practice, the subsea pipelines are welded within 12 m or 24 m segments and therefore the series system reliability which has been formulated earlier is used for the pipeline reliability analysis. The offshore pipeline thickness is calculated based on API rule and for the onshore section from landfall to plant area, ASMEB31.8 code is the normal practice for thickness and stress analysis. There is also an intermediate section called Shore Approach in the submarine pipeline in which the soil is truncated and in some lengths the subsea pipe is backfilled on a soft sand layer. The rest of shore approach section is placed on the trenched channel and normally is not filled with soil. The lengthiest section of pipe from the end of shore approach to offshore platform is usually rested on the seabed.

At the first stage, the element reliability is calculated based on the DNV and API design rules. The shore approach section has 2400m length and it is modeled with 100 and 200 elements using pipe sections of 24 m and 12 m respectively. The rest of subsea pipeline with 105 km length is modeled with 4375 and 8750 pipe section with the length of 24 m and 12 m respectively. The whole analysis is thus done in one element level and 4 system levels with the number of sections given above. Since the wall thickness is different for offshore and onshore parts, the results of pipeline integrity are estimated by adopting offshore and onshore wall thickness selection.

Between the characteristics of pipe, the material strength is assumed as lognormal distribution and its thickness is selected as normal variable. The design pressure is adopted as Gumbel distribution and the rest of variables are assumed as deterministic parameters. In system reliability analysis, the material strength parameters are assumed independent from each other and the design pressure is selected as common random variable for all pipeline segments.

The distribution parameters of strength and pressure variables are given in the following table:

Table 1: Random Variables

Variable Name	σ_y =S	U	$f_{y,temp}$	t_1	t_2	p_d
Variable type	Log Normal	Log Normal	Log Normal	Normal	Normal	Gumbel
Mean	483.84 MPa	572.4 MPa	25.92 MPa	20.6 mm	28.6 mm	14.595 MPa
Standard Deviation	29 MPa	34.34 MPa	1.55 MPa	0.412 mm	0.572 mm	0.728 MPa

The deterministic parameters of geometrical characteristics, the minimum yield and ultimate strength, the effect of de-rating values for yield and ultimate strength, the design temperature for gas flow and other safety factors included in DNV and API codes are given in the following table:

Table 2: Nominal Parameters and deterministic variables

Parameter	D	σ_y=S	U	$f_{y,temp}$	T	a_u	γ_m	γ_{SC}	γ_{inc}	f_d	f_e	f_t
Value	0.8128 m	448 MPa	530 MPa	24 MPa	90°	0.96	1.15	1.138	1	0.9	1.0	1.0

RESULTS

1- DNV RULE

In this section, the reliability analysis results are presented for limit state functions based on DNV rule and having two different thicknesses for submarine pipelines. The reliability indices and probability of failure based on DNV standard is given in the following table:

Table 3: Reliability indices and Failure Probabilities based on DNV rule, t=20.6 mm

N, number of series system segments	1	100	200	4375	8750
Reliability index, β	3.4744	2.4414	2.3114	1.7992	1.6960
Failure Probability, P_f	0.256×10^{-3}	7.3×10^{-3}	1.04×10^{-2}	3.60×10^{-2}	4.49×10^{-2}

Based on the wall thickness calculated for the onshore zone (t=28.6 mm), the reliability indices and failure probabilities are calculated in the following Table:

Table 4: Reliability indices and Failure Probabilities based on DNV rule, t=28.6 mm

N, number of series system segments	1	100	200	4375	8750
Reliability index, β	5.9665	5.2679	5.1739	4.7937	4.7157
Failure Probability, P_f	0.121×10^{-8}	6.90×10^{-8}	1.146×10^{-7}	8.188×10^{-7}	1.204×10^{-6}

2- API RULE

The same procedure is repeated for the reliability formulation based on API design rule. The results of failure probability and reliability index are submitted in the following table.

Table 5: Reliability indices and Failure Probabilities based on API rule, t=20.6 mm

N, number of series system segments	1	100	200	4375	8750
Reliability index, β	2.34	0.9438	0.7704	0.0928	-0.0427
Failure Probability, P_f	9×10^{-4}	1.726×10^{-1}	2.205×10^{-1}	4.63×10^{-1}	5.17×10^{-1}

Table 6: Reliability indices and Failure Probabilities based on API rule, t=28.6 mm

N, number of series system segments	1	100	200	4375	8750
Reliability index, β	5.088	4.3076	4.2057	3.7977	3.7147
Failure Probability, P_f	0.181×10^{-6}	8.25×10^{-6}	1.30×10^{-5}	7.302×10^{-5}	1.017×10^{-4}

Correlation between pipeline failure events depends on several factors, but one of the most important factors is the type of data used as basis for the probability distributions for thickness, yield stress and internal pressure. If a pipeline is very often made of steel from one batch, and these data are based on measurements from a single batch too, then the yield stresses and thicknesses will be independent between pipeline elements.

The correlation of limit state function of individual elements has important effect on the failure probability of series pipeline system [6]. This calculated probability of failure for most likely to fail element (single element) differs very much with the system failure probability using any kind of limit state formulation. Using a common random variable for extreme internal pressure by Gumbel distribution and independent random variables for pipeline thickness and yield strength, the failure probability of series system will fall between upper bound of mutually independent failure elements and the lower bound of maximum failure probability of fully correlated failure element.

The pipe thickness has significant effect on the failure probability of single and series system. Since the pipe thickness has been calculated based on API design rule without allowing any fabrication tolerance, the unreliability of pipeline system on the basis of the calculated wall thickness is evident using API limit state function given in Table 5.

In probabilistic design format for pipeline system, the calculated probability of failure is often compared with the *target* failure probability. The target failure probability depends on the acceptable risk of failure, the consequences of structural failure on the undamaged section called the redundancy of the structural system. Based on the acceptable risk criteria's given in DNV, API rules, a minimum target failure probability of 1×10^{-3} or reliability index as order of 3.09 is selected for the pipeline system. Comparing the reliability results based on API and DNV codes, the calculated failure probabilities will fall in the acceptable region using DNV formulation while it indicates unreliable failure estimate based on API limit state function.

The reliability analysis shows the relative importance of selected limit state function for failure probability estimation in element and system level. Comparison of the failure probabilities of submarine pipelines based on DNV and API rules indicates a homogeneous variation of reliability indices based on DNV limit state design. A similar conclusion has been drawn for reliability analysis of compressed tubular sections with a goal of comparison of Eurocode and API-RP2A-LRFD code format [7].

CONCLUSIONS

1- Using a common random variable for extreme internal pressure by Gumbel distribution and independent random variables for pipeline thickness and yield strength, the failure probability of series system will fall between upper bound of mutually independent failure elements and the lower bound of maximum failure probability of fully correlated failure element.
2- The pipe thickness has significant effect on the failure probability of single and series system.
3- Comparing the reliability results based on API and DNV codes, the calculated failure probabilities will fall in the acceptable region using DNV formulation while it indicates unreliable failure estimate based on API limit state function.
4- The reliability analysis shows the relative importance of selected limit state function for failure probability estimation in element and system level. Comparison of the failure probabilities of submarine pipelines based on DNV and API rules indicates a homogeneous variation of reliability indices based on DNV limit state design.

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