A COMPARISON OF A 3 DIMENSIONAL PROBABILISTIC METHOD OF BERTHING STRUCTURE DESIGN AND THE TRADITIONAL METHOD OF A BERTHING STRUCTURE DESIGN

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ABSTRACT

Finite element method (FEM) is increasingly applied as a first choice tool for designing structures. The same trend is seen in probabilistic designing. Consequently, the application of the combination of these two methods is discussed in this paper.In this study the presence of potential overcapacity in a structure has been studied. As an example the design of an existing berthing structure has been taken. This structure has been designed using Dutch standards and has been redesigned with a Monte Carlo simulation. Remodeling has been done with the help of FEM. The aim of this study is to optimize the capacity for a more economic design. In the simulation the combination of these methods has been applied on a dynamic berthing process of a bulk carrier into an ongoing berthing structure with the help of a static model in FEM. The following variables has been used and studied in the model: the soil characteristics, the characteristics of the cross sections of the berthing structure, the location of impact and characteristics of the vessel that berth at the structure.In conclusion, a three dimensional model made in FEM Scia-engineer, improves the possibility to indicate the critical variables and overcapacity of elements in a model of the berthing structure.

Keywords: Probabilistic design, Finite Element Method, Saurin, P-Y curves

1. INTRODUCTION

There are many ways to design a structure. The traditional deterministic method assumes standard values and standards. The probabilistic method assumes variables for values of strength and loads. With help of the probabilistic design method it may be possible to save capacity and consequently costs are reduced.

The system is described by the berthing of a vessel, with a variable kinetic energy, which is transformed to potential energy by a berthing structure. A minimum chance of failure prescribed by NEN6700 is desirable.

We consider the chance of failure for every design method and match the amount of capacity. Calculating the chance of failure there are 3 levels: level 1 (deterministic), level 2 (semi-probabilistic) and level 3 (probabilistic). In this paper we compare level 1 with level 3.

We have been using a Finite Element Method (FEM) as calculation tool [1.]. This FEM has been designed to calculate deterministic and statically models in 3 dimensions. This FEM has been used to simulate a dynamic system. The input has been stochastic. Therefore this FEM has been part of a probabilistic model. Using this type of FEM makes it possible to consider the berthing structure in parts. Thus insight is given in optimizing all variables of the system. In this paper first the research question is presented followed by some brief theoretical background and a description of the methods. Afterwards we consider the results, discussion and conclusion.

2. RESEARCH QUESTION

The main question is: “Is there any difference in results between the traditional method of design and the 3 dimensional probabilistic method of design?”. Several parts of the design have been tested. The final minimum of capacity has been determined by the results of these tests. The main question has been divided by the following sub-questions: What is the difference between methods of design in: (1) maximum of exceeding, (2) the strength of the steel elements, (3) Level 3 sensitivity analysis and (4) chance of failure of the probabilistic system?

3. THEORETICAL BACKGROUND

First a brief explanation of the probabilistic theory is given followed by an explanation of the physical behavior of the structure.

Probabilistic theory

For calculating the total chance of failure all relations and their hierarchy should be known. This is done with help of a fault tree. The limit state has been used calculating the chance of failure of every mechanism. There are three different ways of interpreting of the limit state (level 1 to 3). These terms are discussed below.

Fault tree

The fault tree shows the main mechanism for failure and their relationship to each other. The chance of failure is calculated with help of the limit-state. The relationship of the sub-mechanisms with the main event is shown in Figure 1. The fault tree includes both the deformation and the moment of reaching the yielding stress as a failure mechanism. The relationship between the sub-mechanism in a fault tree can be described as a serial or parallel.

Ditlevsen

The system that is considered in this paper has been taken as a serial system. That means that when one sub-mechanism has failed the main event is considered to have failed. A method to investigate a serial system is the method of Ditlevsen [2.]. The method of Ditlevsen assumes a correlation between the sub-mechanisms, expressed by a correlation coefficient ρ. The boundaries of failure in this paper are considered having a correlation of ρ=0 of ρ=1.

Limit State

The chance of failure (P_f) of the systems has been determined by means of the limit state function (see (1)). The strength (R) is compared to the loads (S) in the limit state. The measure of failure is expressed as Z. Positive values of Z mean non failure and negative values mean failure. The methods of calculating the limit-state has been done at different levels: level 1 (deterministic), level 2 (semi-probabilistic) and level 3 (probabilistic).

$$Z=R-S \quad (1)$$

Level 1

Level 1 is used in the Dutch standards. A certain margin has been used between the representative value of loading and the representative value of strength. The design point (Z=0) is the value in the distribution of strength and load with the greatest common probability density. The representative value of strength is divided by an safety factor and the representative value of loads is multiplied by a safety factor (see (2)).

$$\frac{R_{rep}}{\gamma_R} > \gamma_S S_{rep} \quad (2)$$

Level 3

In this method the Crude Monte Carlo (MC) has been used. The size of failure has been determined by means of the limit-state function (see (3)).

$$Z=g(x)=R(X_1,X_2,X_m)-S(X_1,X_2,X_m) \quad (3)$$

The negative values of Z correspond to ‘failure’ and the positive values of Z correspond to ‘non failure’ (see (4).

$$\mathrm{P_f} = \mathrm{P}[\mathrm{g}(\mathrm{x}) \leq 0] \quad (4)$$

The reliability index is found by the following equation (see (5)).

$$\beta = \Phi^{-1}(\mathrm{P_f}) \quad (5)$$

Φ expresses the normal distribution. For values of X some variables have been taken as a distribution function and some values have been taken as fixed values (deterministic values). The chance of failure (P'_f) that is expected of a structure with a reference time of 50 years and safety class 2, is in the order of $P'_f=10^{-4}$. The amount of calculations is determined by equation (6)[2.].

$$\mathrm{N} > 400(\frac{1}{\mathrm{P_f}} - 1) \quad (6)$$

This results in a large amount of calculations (ca. 3999600 runs). One run takes about 15 seconds. This would take too much time. In this study 8000 runs for loading and 122 runs for strength has been used.

4. BEHAVIOR OF THE SYSTEM

In this paper the FEM that has been used calculates only static systems. The system that is considered has been described by means of a dynamic energy equation. In order to tackle this problem an energy equation

(E_k=E_p) has been used that has been defined to a statical equation which includes force (F). The load has been determined according to a kinetic equation (see (7)), in which m [DWT] describes mass and v [m/s] is speed of the vessel.

$$E_k = 0.5 * m * v2 \quad (7)$$

The maximum energy of absorbed energy has been determined with a potential elastic energy equation (see [8]).

$$E_{pot} = 0.5 * k * x^2 \quad (8)$$

The k [kN/m] describes the spring constant and has been determined by the stiffness of the structure. At the moment that the largest deformation occurs x [m], the largest force F [kN] will occur.

Behavior of the load

The load of energy has been introduced by means of the application of the equation of Saurin[3]. This equation describes the occurring kinetic energy of the mooring vessel. The equation of Saurin describes the influence of the local condition as factors. The load depends on: (1) mass of the vessel [DWT], (2) speed [m/s], (3) length of vessel [m], (4) width of the vessel [m], (5) vessel depth [m], (6) berthing angle [^{0}], (7) location of berthing [m] and (8) local depth of the water [m].

Strength

The total structure exists of soil and steel piles. Regarding the soil-model p-y curves were used [4.]. The p-y curve has elastic and a plastic track, where the stiffness of the soil depends on the following functions: (1) type of soil, (2) angle of internal friction, (3) cohesion en (4) the depth of the soil. The p-y curves can be schematized as springs that function independently of each other. The depth where still a stability of the pile in the soil is assumed to exist determines the depth of the piles. The method of Blum uses the full plastic soil behavior and says that the minimum pile depth is found at the equilibrium of shear forces[5.]. The strength of the steel structure has been tested for the occurring stress caused by the occurring moment. The local buckling has been taken in to account [6.]. This test is a function of the following cross section characteristics: (1) wall thickness of the piles [mm], (2) the pile diameter [mm], (3) yielding stress [N/mm^2].

5. METHODS

As reference an already existing birthing structure was taken, the Lyondell jetty in the port of Rotterdam [7.]. The structure was calculated conform the EAU2004 and the NEN6700 [3.] [7.] [9.]. Because the EAU2004 refers to the DIN EN 1900, in the Netherlands this is the NEN-EN1900. Knowing this, it can be concluded that the Lyondell jetty is built according to the Dutch used safety rules. The NEN6700 are more economical orientated then the NEN-EN1900. The safety considerations of the NEN6700 are adopted accordance safety class 2. The Lyondell jetty was redesigned because of the difference in soil modeling. In the existing calculation of the berthing structure a different soil modeling was applied, a new design was made in reference to the Lyondell jetty [7.] [8.]. In this design some adaptations were made in order to improve the applicability of the model. The pile was adapted and the berthing structure was stretched in order to prevent eccentric loading. The berthing structure (beam) was assumed to water level and the wooden grid has been removed to prevent eccentric loading. The probabilistic model had tested the found values of the newly designed berthing structure of the Lyondell jetty.

Probabilistic model

- Determination of the distributions:
  Due to the limitations of the use of Microsoft Excel as a random number generator distributions 8. till 12. were adjusted to
- *Determination of the load:* By use of the equation of Saurin, the energy load was determined by 8000 runs. With help of the FEM and Microsoft Excel as executer a data file was made. As input the variables of strength (122 runs) and successive loads (200-4800 kN with steps of 200kN) per location were used in the FEM. By means of the calculated deformation and the occurring loads the absorbed potential energy was determined per location at the berthing beam (1meter grid).
- *Determination of strength:* Based on drawn values of wall thickness and steel strength by use of the analytical equation of ultimate occurring moment the capacity of strength was determined. Both failure mechanisms of deformation and strength were considered independent.
- *Determination of the coupled values:* Based on the generated data the similarities of load size and the location of the occurring load were matched. That is, the results of the equation of Saurin and the calculated loads of Scia Engineering (FEM) were matched.
- *Use of the limit-state:* In the previous step the occurring load was matched with the corresponding strength. Filling in the limit state equation the amount of failure was calculated per run (Monte Carlo).

- *Data interpretation:* The data were interpreted with help of the tests in order to achieve a corresponding distribution. With this distribution the chance of failure was determined.
- more appropriate normal distributions (see Table).

Table 1. Adopted distributions.
DWT: vessel weight in tons, Velocity: perpendicular to the berthing structure, Angle of berthing: angle between vessel and the berthing structure and Berthing off-set: favorable position for loading

Parameters	Dist. type	mean	Standard deviation
1.Vessel weight [DWT] [8.]	Normal	38050	9025
2.Berthing velocity [m/s] [8.]	Gumbel	$1.9247*DWT^{-0.3003}$	$0.44*1.9247*DWT^{-0.3003}$
3.Angle of berthing [^{0}] [8.]	Normal	7.5	1.25
4.Berthing offset [m] [8.]	Normal	0	2.5
5.Length (LOA) [m]	Normal	$9.1647*DWT^{0.2861}$	$3.6091*DWT^{-0.4020}$
6.Draft (D) [m] [8.]	Normal	$1.2958*(DWT/LOA)^{0.4065}$	$0.2062*(DWT/LOA)^{-0.2235}$
7.Width [m] [8.]	Normal	$3.1088*(DWT/LOA*D)^{0.7732}$	$0.7414*(DWT/LOA*D)^{-0.8610}$
8.Soil weight [kN/m^3] [8.]	Normal	$\gamma_{saturated}$	$0.01*\gamma_{saturated}$
9.Angle of friction [^{0}][8.]	Normal	$\varphi_{saturated}$	$0.2*\varphi_{saturated}$
10.Drained cohesion[kN/m^3][8.]	Normal	$c_{u,calculated}$	$0.25*c_{u,calculated}$
11.Steel yielding strength [N/mm^2] [8.]	Normal	$f_{sp}*1.52-20$	$0.07*(f_{sp}*1.52-20)$
12.Wall thickness [mm] [8.]	Normal	$t_{ordered}$	$0.1*t_{ordered}$

6. RESULT

The following parameters were examined to point out the difference in capacity between the traditional method of design and the probabilistic method of design (sub-questions): deformation, strength, Level 3 sensitivity analysis and the total chance of failure of the structure according to the probabilistic designed structure.

Deformation

A boundary of approximately 0.7m was taken in the deterministic design for maximum of deformation. This was tested for a collision with the bow and with the stern of the vessel (see Table 2). Because of the term “approximately” the chance of failure with a boundary of 0.8m was tested as well (see Table 2).

Table 2. Comparison of chance of failure between the design with level1 and level 3. Level 3 bow: collision at the bow area, level 3 stern: collision at the stern area.

	Level 3 bow	Level 3 bow	Level 3 stern	Level 1
Maximum deformation	0.7m	0.8m	0.7m	0.7m
Chance of accidence	$1.56*10^{-2}$	$2.9*10^{-3}$	$1.4*10^{-2}$	$3,54*10^{-2}$

In the results this was not explicitly presented, but the moment of contact with the vessel and the berthing structure is between 31m and 64m measured from the loading arms. This principle applies to both the bow and the stern.

Strength

For both designs the chance of failure was tested. It was assumed that the whole structure, designed according the NEN6700, will suffice according to the safety philosophy of the NEN6700. A distinction was made between the berthing beam and the piles in calculating failure chance (see Table 3). Calculating the chance of failure of the piles, it was assumed that the berthing beam had already failed and preserved its elastic behavior.
The results show the realistic distribution (Weibull distribution) and the appliance of a Normal distribution. The chance of failure was calculated with help of the normal distribution (see Table 3).

Table 3. Comparison of the reliability indices, the chance of failure probabilistic (*1) and the deterministic design (*2) of the total structure and the piles.
Pf’ is the chance of failure in 50 years, berthing frequency of once a week.

	Bow (β) Weib.(*1)	Bow (β) Norm.(*1)	Bow Norm. P_f' (*1)	stern(β) Weib.(*1)	Stern (β) Norm.(*1)	Stern norm. P_f' (*1)	Total (β) (*2)	Total P_f' (*2)
Total structure	5.03	3.4	$3.63*10^{-4}$	6.4	2.9	$2.1*10^{-3}$	3.4	$P_f=3,37*10^{-4}$
piles	6.7	3.6	$1.58*10^{-4}$	7.4	4.6	$2.56*10^{-5}$	3.4	$P_f=3,37*10^{-4}$

Level 3 sensitivity analysis

The following analysis was made of the correlation according to the classical sensitivity method. A correlation was determined between the reliability equation and the basic variables.

Table 4. Correlation coefficient between basic variables of the energy loading of the vessel and the reliability function

Variable	Mass [DWT]	Vel [m/s]	L [m]	W [m]	D [m]	Angle [^{0}]	Coor [m]	E [kNm]
ρ	-0.12	-0.55	-0.102	0.055	-0.099	0.004	-0.016	-0.57
ρ^2	0.01	0.3	0.01	0.003	0.001	$1.6\text{-}10^{-6}$	$2.5*10^{-4}$	0.32

Table shows a clearly recognizable negative correlation of the energy (E). The speed as well as the thickness of the wall (t=22.2 [mm]) and the yielding stress (f_y=380[N/mm^2]) show a clear correlation with the reliability function (see Table 4 and Table 5). The wall thickness of t=22.2 [mm] and t=30 [mm] have both a positive relation with the reliability function. Wall thickness t=22.2 [mm] and the steel quality of f_y=380[N/mm^2] show a similar correlation (see Table 5). Both are values of the beam. The wall thickness of t=30 [mm] and t=40 [mm] are the thicker parts of the pile and show a negative correlation. The Width (W), Draft (D), Angle and Coordination offset (COOR) have a very small correlation.

Table 5. Correlation coefficient between basic variables of strength (wall thickness and yielding stress) and reliability function

Variable	t=22.2[mm]	t=30[mm]	t=38[mm]	t=40[mm]	f_y=380[N/mm^2]
ρ	0.68	0.44	-0.37	-0.25	0.68
ρ^2	0.46	0.19	0.14	0.06	0.46

Failure of the total structure

Figure 1 shows the chance of failure in the fault tree, both dependent as well as independent. The Service Limit State (deformation) was dominant in the failure chance of the Main Event. The chance of failure of the berthing beam due to loading of the stern was about 10 times larger than the loading of the bow.

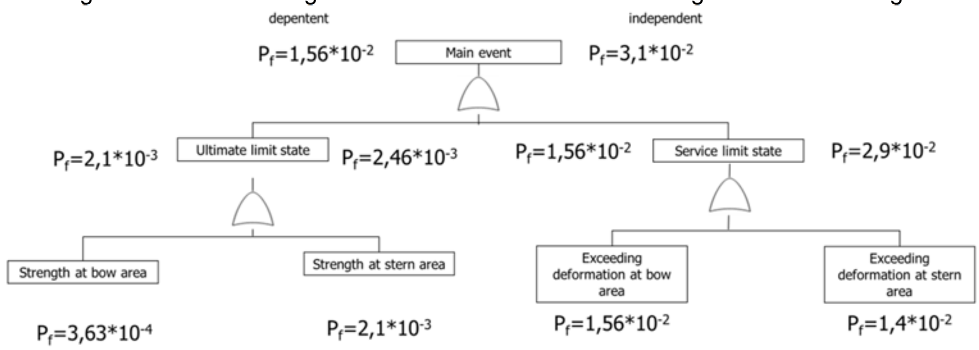

Figure 1. Fault tree of the probabilistic method

7. DISCUSSION

- *Deformation*: The probabilistic design exceeds the allowable chance of failure prescribed by the NEN6700 in a maximum deformation of "approximately" 0.7m. With a maximum deformation of 0.8m the chance of failure is equally high or less high. The reason of the chosen boundary of deformation is not explicitly known. A possible explanation might be that the reachability of the loading arms is limited to 0.7m. If the reachability can be increased by 0.1m, the chance of exceeding the design value significantly decreases. The structure probably acts more stiff at the stern probably because of the ongoing beam. The interaction surface is very local.
- *Strength*: The chance of failure of the total berthing structure (probabilistic model) exceeds the prescribed chance of failure of the NEN6700 (see Table 3). Further analysis shows that this is caused only by the berthing beam. If the berthing beam is allowed to have plastic deformations the piles will be continued to

be loaded. Due to the overloading of the beam and its plastic deformation the berthing beam will absorb even more kinetic energy. However in the model the beam will keep it is elastic behavior when it is overloaded. The chance of failure of the piles is significant smaller than the chance of failure of the beam.

- *Level 3 sensitivity analyses*: The positive correlation show that the two wall thicknesses of t=22.2 [mm] and t=30[mm] and the steel quality of f_y=380[N/mm^2] in the model are chosen too small. The wall thickness and yield stress are values of the beam. The beam was indicated as the critical factor before in the strength analyses. The wall thickness of t=38[mm] and t=40[mm] are the thicker and stiffer parts of the piles. From the negative correlation it appears that these parts are too stiff and make the moment concentrate more around these parts. This probably causes the weaker parts around them to fail at the transition between the pile sections. But the values are very small. The values of Length, Width, Draft, Angle and Coordination offset of the vessel are very small and it could be that they are only sound.
- *Failure of the total structure*: in this system the exceeding of the design deformation and failing the elastic strength will lead to the same main event. The exceeding of the design deformation is the dominant failure factor shown in the fault tree (see Figure 1). Earlier it is said that the prescribed maximum deformation of 0.7m is considered to be very small. When the fender has the possibility to allow more deformation, this boundary is enlarged and the chance of failure of the main event will correspond more with the chance of failure of the strength. It will also be possible to make the berthing structure less stiff, which means that less capacity is needed. With an exceeding of the maximum deformation the jetty will experience damage and it will be necessary to take it out of service. Here are more costs involved than repairing the plastic deformation of the berthing beam. The use of the service limit-state in calculating the deformation is perhaps unjustified.

8. CONCLUSION AND RECOMMENDATIONS

The comparison between the traditional method of design and the 3 dimensional probabilistic method of design shows that the applied load on the structure is concentrated around the interaction surface area between the structure and the vessel. The capacity outside this interaction surface adds little to the absorbing of the energy. The analyses of the berthing process shows that the chance of failure of the berthing of the bow is a factor 10 smaller than the chance of failure of berthing with the stern. If the unnecessary berthing beam and piles outside the interaction surface, are left out, the structure will react less stiff and the chance of failure of berthing with the stern will decrease.

The chance of failure of the main event can be reduced by changing the prescribed maximum deformation from 0.7m to a larger deformation. This can be achieved by increasing the reachability of the loading arms. So it is possible using the energy equation to its optimum. The sensitivity analysis shows that the beam should have more capacity and the piles should have less stiffness. And extra attention should be paid to the transition area between the thicker and thinner parts of the piles. Using the 3 dimensional probabilistic method of design gives more insight in the exact details and factors to optimize.

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