Study on Optimization Model of Truss Structure under Different Constraints

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Abstract. The paper takes the real jacket offshore platform as an example. The structural finite element software structural analysis was used to establish the structural section optimization, shape optimization and shape optimization model based on component reliability. The results reflect that the shape optimization efficiency based on component reliability is high under the premise of guaranteeing the reliability of the structure. Therefore, preference should be given to the structural shape optimization considering reliability in the engineering.

1. Introduction

Structural optimization is a method to reduce engineering cost based on structural performance and safety. It can be divided into structural section optimization, structural shape optimization and structural topology optimization [1] and structural reliability constraint optimization considering structural optimization with the deepening of structural theory research and optimization focus. Structural optimization design originated in the early 1960s. A milestone of development is that Schmit first solved the structural optimization problem in a mathematical way and proposed a solution method [2]. Since then, a lot of meticulous theoretical studies has been carried out at home and abroad and fruitful results have been achieved. GU Yuan-Xian et al [3] proposed the problems of sequence linear programming to receive member size parameter and structure shape parameter in shape optimization. Du XP et al [4] proposed using optimized sequence algorithm to solve the problem of reliability analysis in optimization constraints. Tang Dong-Feng et al [5] considered structural reliability in continuum topology optimization, and introduced reliability into optimization design in theory and engineering practice.

Many related researches are conducted on the selection of structural optimization models [6-7], and there is still a lack of research on the comparative analysis of the optimization effects of different optimization models. In this paper, the actual jacket offshore platform is taken as an example to compare various optimization. The research results have reference value and significance on the optimization design of jacket offshore platform and similar truss structure.

2. Optimization models

The major structure of offshore oil production platform is steel truss which has complex structure and high cost. The main task of structural optimization design is to optimize the structure, reduce the cost and improve the reliability of the platform structure. It has important theoretical and applied value.

2.1 Original platform structure model
In this paper, the example of Shengli Oilfield No. 11 jacket offshore oil production platform is the real engineering and optimization research object of the truss structure. Shengli Oilfield Chengbei No. 11 is a typical fixed jacket platform. The structure diagram is shown in Figure 1. The plane of the jacket platform is a regular quadrilateral with a pile spacing of 11 meters and a pile depth of 25 meters. The cross-section dimensions of piles, duct legs, chords, struts, etc. about design initial value are shown in Table 1.

Table 1. Sectional dimensions of the major members of the jacket

| Component name          | Pile | Catheter leg | Chord | Support rod |
|-------------------------|------|--------------|-------|-------------|
| Outer diameter          | 0.800| 1.030        | 0.529 | 0.426       |
| Wall thickness          | 0.020| 0.015        | 0.007 | 0.007       |

2.2 Section optimization model

The purposes of Section optimization are to meet the requirements of the structural force constraints and to strive to rationalize the structural section and to reduce the cost with the minimum quality as the optimization goal. The variables of cross-section optimization has the outer diameter and wall thickness of the circular section of the conduit.

Find $X = (X_1, X_2, \cdots, X_n)^T$

Min $f(X)$

s.t. $g_j(X) \leq 0, \ j = 1,2,\cdots, n$

$X^L_i \leq X_i \leq X^U_i, \ i = 1,2,\cdots, n$ (1)

There, each $X_i$ is the outer diameter and wall thickness of each type of conduit, $X^L_i$ and $X^U_i$ are upper and lower limits.

2.3 Shape optimization model

In addition to the section optimization, the optimization of the truss structure include that the node position of the structure is reasonable or not which affects the analysis of the structure stress directly and affects the structural mass and cost.

When using the structural mass of a general truss structure as the objective function, then the shape optimization model can be written as:

Find $x : R^n$ $D$ $t : R^n$

Min $W(D,t,x) = \sum_{i=1}^{j} \rho_i l_i(x_i) f_i(D,t)$

s.t. $\sigma_{\text{max}i} - [\sigma] \leq 0$

$\sigma_{\text{c max}i} - [\sigma_c] \leq 0$

$u_{\text{max}} - [u] \leq 0$ (2)

In each load condition, $\sigma_{\text{max}i}$ is the maximum normal stress of the rod $i$; $\sigma_{\text{c max}i}$ is the maximum compressive stress; $u_{\text{max}}$ is the maximum node displacement; $l_i$ is the length of the bar $i$; $X$ is the design vector of jacket truss node coordinates. $f_i(D,t)$ is the cross-sectional area of each rod.

Since the optimization model involves two kinds of different nature variables which are the component size variable and the structural geometry variable, a sequence secondary optimization method based on the design variable hierarchy can be used for such problems.

2.4 Shape optimization model based on member reliability
Find \( x : R^n \), \( D, t : R^m \)

\[
\text{Min} \quad W(D, t, x) = \sum_{i=1}^{j} \rho_i l_i(x_i) f_i(D, t)
\]

\[
\text{s.t.} \quad \begin{align*}
\sigma_{\max} & - [\sigma] \leq 0 \\
\sigma_{\text{c,max}} & - [\sigma_{\text{c}}] \leq 0 \\
u_{\max} & - [u] \leq 0 \\
[\beta] & \leq \beta_j
\end{align*}
\]

Where \([\beta]\) is the target reliability indicator and

\[\beta = \frac{Z}{\sigma_j} = \frac{\bar{R} - \bar{S}}{\sigma_R + \sigma_S} \]  \( \text{Where:} \ \bar{R}, \ \sigma_R, \ \bar{S}, \ \sigma_S\]

\(\sigma_S\) are the mean value and standard deviation of \( R \) and \( S \) respectively. The value of \( \beta_j \) should be determined according to the safety level of the structure and the type of damage.

3. Examples and comparison
The previous article takes Shengli Oilfield No. 11 Steel Jacket as an example and the optimization models are as shown in formula(I) (II) (III).

3.1 Platform load
The load conditions of the jacket offshore platform are shown in Table 2, and the combinations of load case are listed in Table 3 and Table 4.

| Load condition | FX (KN) | FY (KN) | MX (KN·m) | MY (KN·m) |
|----------------|---------|---------|------------|------------|
| 1              | 34.86   | 0       | 0          | 661.64     |
| 2              | 43.73   | 43.73   | 830.08     | 830.08     |
| 3              | 671.83  | 0       | 0          | 12751.33   |
| 4              | 432.52  | 432.52  | 8209.23    | 8209.23    |
| 5              | 173.59  | 0       | 0          | 1024.18    |
| 6              | 122.75  | 122.75  | 724.21     | 724.21     |
| 7              | 826.65  | 0       | 0          | 7274.52    |
| 8              | 823.66  | 823.66  | 7248.20    | 7248.20    |
| 9              | 1537.55 | 0       | 0          | 29059.70   |
| 10             | 0       | 1537.55 | 29059.70   | 0          |

Note: The moment in the table is the simplified force of the mud surface.

| Serial number | Load combination |
|---------------|------------------|
| 1             | Ice + wind + flow + maximum vertical load + design high water level (45°) |
| 2             | Ice + wind + flow + maximum vertical load + design high water level (45°) |
| 3             | Ice + wind + flow + partial vertical load + design high water level (45°) |
| 4             | Wave + wind + flow + maximum vertical load + design high water level (0°) |
| 5             | Wave + wind + flow + minimum vertical load + design high water level (0°) |
| 6             | Earthquake (8°) + maximum vertical load + design high water level (45°) |
Table 4. The combined value of load in each combination

| Serial number | FX(KN)  | FY(KN)  | FZ(KN)  | MX(KN·m) | MY(KN·m) |
|---------------|---------|---------|---------|----------|----------|
| 1             | 900.63  | 900.63  | -10780  | 8357.57  | 8357.57  |
| 2             | 900.63  | 900.63  | -1960   | 8357.57  | 8357.57  |
| 3             | 900.63  | 900.63  | -3920   | 8357.57  | 8357.57  |
| 4             | 880.28  | 0       | -10780  | 0        | 7003.47  |
| 5             | 880.28  | 0       | -1960   | 0        | 7003.47  |
| 6             | 1537.55 | 1537.55 | -10780  | 29182.70 | 29182.70 |

Due to the lack of data on the windshield area of the platform, the wind load values directly quote the literature [10].

3.2 Cross section optimization results

The initial values, upper and lower limits of each optimization are shown in Table 5, and the list of optimization results is shown on table 6.

| Component name     | Pile | Catheter leg | Chord | Support rod |
|--------------------|------|--------------|-------|-------------|
|                    | lower| upper        | lower| upper       |
| Outer diameter     | 0.800| 1.000        | 0.850| 1.100       |
| Wall thickness     | 0.015| 0.030        | 0.015| 0.020       |

The optimization in ANSYS gives the results as shown in Table 6 below.

| Target letter      | Design variable |
|--------------------|-----------------|
| Value W(N)         | D1(m) D2(m) D3(m) D4(m) |
| Original design value | 10.99E5 0.800 1.030 0.529 0.426 |
| Section optimization value | 8.93E5 0.800 0.851 0.630 0.254 |
| Shape optimization value | 7.77E5 0.560 1.067 0.354 0.301 |
Reliability shape optimization

| T1(m) | T2(m) | T3(m) | t4(m) | ZA(m) | ZB(m) |
|-------|-------|-------|-------|-------|-------|
| 0.020 | 0.015 | 0.007 | 0.007 | -25.00| 3.50  |
| 0.015 | 0.015 | 0.007 | 0.007 | ——    | ——    |
| 0.015 | 0.015 | 0.007 | 0.008 | -28.00| 5.00  |
| 0.016 | 0.015 | 0.007 | 0.007 | -25.00| 5.00  |

4. Comparative analysis of optimization results

Section optimization values is rational compared with the original design value. The outer diameter of the catheter leg is reduced by 17.3% and the outer diameter of the diagonal bracing is reduced by 40.3%. The wall thickness is reduced by 25% when the outer diameter of the pile is not changed, at the same time the outer diameter of the chord is increased by 10cm while maintaining its wall thickness. The results reflect that the flexibility of the structural member is increased and the truss structure needs a larger lateral connection to increase the whole lateral stiffness of the platform effectively after the optimization of the section.

Shape optimization has the highest efficiency which is 29.3% smaller than the original design and 13.0% smaller than the cross-section optimization results of total mass.

The shape optimization efficiency is the third level and the weight is 15.7% lighter than the original design after optimization based on the reliability of structural members.

It can be seen from the list that the efficiency of shape optimization and section optimization is more efficient than the shape optimization based on member reliability when using the structural weight as the optimization target. The reason is that shape optimization and section optimization do not consider the reliability of the structure and optimizing higher efficiency is achieved at the expense of structural reliability. Table 7 as below is the reliability indicators and failure probabilities of the most dangerous members under the load working condition 1 after comparing the optimized structure of each model.

Table 7. The comparison of the reliability indicators among the most dangerous members in optimization results

| Optimization model                     | Reliability index $\beta$ | failure probability $P_f$ |
|----------------------------------------|---------------------------|--------------------------|
| Section optimization                   | 2.12                      | 1.7E-2                   |
| Shape optimization                     | 0.299                     | 3.84E-1                  |
| Shape optimization based on component  | 3.20                      | 6.9E-4                   |
| reliability                            | original design           | 3.35                     |

5. Conclusion

At first, the sequence quadratic optimization method is a very effective solution to the optimization model of two kinds of variables. Secondly, shape optimization is a very efficient structural optimization through comparative analysis, but the structural reliability is not guaranteed after optimization. Thirdly, structural reliability must be considered which is an effective guarantee of the structure when the structure is optimized. Fourthly, member reliability is used in the paper. Component reliability is different from structural system reliability for complex structural systems. Comprehensive research on structural system reliability is the key direction of future research.

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