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Installation Stability of Low Temperature Steel Mesh in LNG Storage

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Abstract**—**To enhance installation security, a LNG storage in Rudong of Jiangsu province was adopted as a practical work, and it was analyzed by nonlinear finite element method to research overall and local stability performance, as well as the stress and deformation under the action of wind load and self-weight. Results indicate that deformation is tiny when steel mesh maintains as an overall ring, and stress caused by vertical bending moment and tension of bottom tie wire are also in the safe range. However, axial forces of lap reinforcement in adjacent steel mesh exceed the ultimate bearing capacity of tie wire. Hence, tie wires are ruptured; single mesh loses lateral connection and turns into monolithic status as the destruction of overall structure. Further more, monolithic steel mesh is led to collapse by the damage of bottom connection. So, in order to prevent connection failure and enhance installation security, the overlapping parts of steel mesh should be taken more reliable measures.

Keywords**—**low temperature steel mesh; installation stability; nonlinear finite element; tie wire.

I. Introduction

In recent years, because of better insulation properties and larger storage volume [1], LNG storage is applied in a large number of practical projects. China has established lots of LNG storages in Shanghai, Xinjiang, Jiangsu and so on [2]. In the world, Tokyo Gas Company plans to spend 206 million U.S. dollars to construct the world's largest LNG storage tanks in Yokohama. With a total capacity of 25 thousands of liters, the project is planned to put into operation in October 2013.

The most important feature of LNG storage is to maintain low temperature, even the lowest can reach -165 [3]. In order to keep stability, low temperature steel bar must be used, which has higher tensile strength (up to 552 N/mm^2) but more sensitive to flaws. So, it is usually linked by bound connection. As storage is building, low temperature steel bar is manufactured into two kinds of steel mesh (inner side and outer flank), which will be lifted to a designated location and connected into an overall ring [4]. After that, exerting prestressing force, putting up template and pouring concrete. It can be seen from the above that overall ring is independent in the stage of exerting prestressing force, as it is only fixed by the bottom bound. Hence, that may lead to installation instability. The instability is ignorable in the state of small wind load but obvious in the state of big wind load. So, it is valuable to research the installation stability of steel mesh.

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II. THEORETIC BASIS

2.1Two types of instability

According to the characteristic of instability, there are two types [5]. The first is linear analysis of elastic model, the second is nonlinear analysis of elastic-plastic model, which considers the influence of material and geometry [6].

In the analysis of the first instability, structure emerges new form of balance, which is essential difference from the form of pre-buckling equilibrium, as well as force and deformation have a sudden change [7]. But, the second instability links structure stability with component strength, which displays structural strength, stability and rigidity in the form of load-displacement curve. In fact, lots of stability problems belong to the second category. Therefore, this article adopts the second instability.

2.2 Criterion of the second instability

There are two kinds, one is yielding criterion of the boundary edge fiber, other one is crushing criterion.

2.2.1 Yielding criterion of the boundary edge fiber

Yielding criterion takes stability factor to determine whether the structure is instability, stability factor is the ratio of actual load to yielding load. According the principle of instability not prior strength failure, the overall stability factor should be greater than the allowable stress safety factor. That is, the minimum stability factor of steel structure should be greater than 1.7 [8].

2.2.2 Crushing criterion

With the increase of load, stiffness of the structure also will be changed. When pressure stress (or shear stress) makes the structure stiffness matrix singular, carrying capacity of the structure reaches the limit [9]~[11]. So, critical load is determined by the extreme point of load-displacement curve, this method is called limit load theory, also known as crushing criterion.

This paper focuses on the safety performance of overall structure and reinforcement yielding, so yielding criterion of the boundary edge fiber is appropriate.

III. PROJECT CASE

A LNG storage in Rudong of Jiangsu province was adopted as a practical work. External diameter is 83.6m while inner diameter is 82.0m; the storage is divided into 11 layers and the top elevation is 39.689m, this paper studies the installation stability of 10th-11th layer. Calculation software is Sap2000V11 [12] and method is non-linear finite element analysis considering P-Detal effect. The whole model is consisted of a huge number of elements (more than 3 millions), so computing device uses high-performance computer of Shanghai Supercomputer Center.

3.1Judgment parameters of instability

For this project, the structure instability can be considered as two situations, one is reinforcement yielding, we can judge it from contrasting internal force to yield limit. Other one is rupturing of tie wires, which may lead to integrated damage. As far as the ultimate bearing capacity of tie wire, we obtain it from experiments, as shown in Table 1.

TABLE I
ULTIMATE BEARING CAPACITY OF TIE WIRE

ultimate bearing capacity	Average value N
single tie wire	192
3 bound connections	2890
4 bound connections	4230

Note: 1."3 bound connections" means the bound amounts of adjacent steel mesh, every bound connection uses double tie wires.
2. Diameter of tie wire is 0.7mm.

3.2 Single steel mesh model

The width of single steel mesh is 10.748m. Height of inner side is 9.314m and outer flank is 3.600m. To connect both sides into a whole, linking reinforcements are emplaced. Furthermore, at the height of 7.100m, 6 additional reinforcements are emplaced. The elevation of mesh bottom is 28.800m and top is 38.114m. Bottom is connected with embedded reinforcements of the ninth layer; the length of connection is 900mm, as shown in Figure 1.

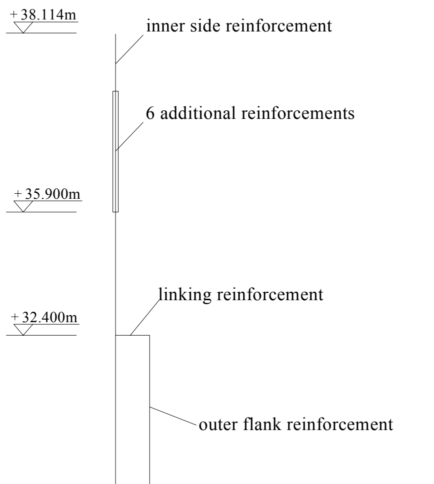

Fig.1 Single steel mesh model

TABLE II
REINFORCEMENT DISTRIBUTION OF SINGLE STEEL MESH

Reinforcement position	Diameter and spacing	Label	value of tensile strength
Inner side (vertical)	Φ25@195.42mm	KRYBAR-165	460N/mm^2
Inner side (horizontal)	Φ25@195.42mm	KRYBAR-165	460N/mm^2
Additional reinforcement	Φ25@195.42mm	HRB335	300N/mm^2
Outer flank (vertical)	Φ25@195.42mm	HRB400	360N/mm^2
Outer flank(horizontal)	Φ25@200.00mm	HRB400	360N/mm^2
Linking reinforcement	Φ16@586.26mm	HRB335	300N/mm^2

The distribution of reinforcement is shown in Table 2.

3.3 Whole model

Model diameter is 82.0m, thickness of concrete cover is 65mm, and the space between both sides is 635mm, as shown in Figure 2.

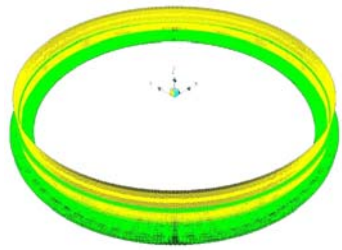

Fig. 2 Whole steel mesh model

3.4 Setting of calculation parameter

(1)Bottom connection (900mm) adopts 3 bound connections, and it is assumed as rigid.

(2)Adjacent steel mesh adopts 4 bound connections to form an overall structure.

(3)In the actual construction, vertical reinforcement is just connected with horizontal reinforcement by tie wire, both of them can produce relative rotate. Hence, it is unreasonable to adopt rigid joint or hinged joint. In order to simulate actual constrains, a new node model called "small rod" is presented, as shown in Figure 3. That is, a small rod is extends at the node of horizontal and vertical reinforcement, both of them are rigid connection. The new model can not only transfer bending moment but also simulate actual eccentricity. Therefore, it is more consistent with the actual situation.

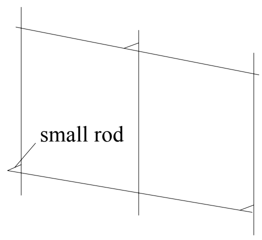

Fig. 3 "Small rod" model (Plum-shaped layout)

(4) wind load calculation

Half of the whole model is divided into three parts. Each part is composed of four steel meshes, as shown in Figure 4. Because the projected area of each part is different, the wind load is different too.

The site classification is category A, the largest wind power reaches 6 and reference wind pressure is 117 N/m^2 (on-site measure). As the steel mesh has a small range of height variation (only 9.314m), wind load can be considered as distributed load. To make the calculation easier and faster, distributed load is converted into point load and applied to nodes [13]~[15]. The calculation result shows that: in part 1, point load of outer flank is 3.43N while inner side is 3.69N; in part 2 and part 3, point load of outer flank is 2.53N while inner side is 2.68N.

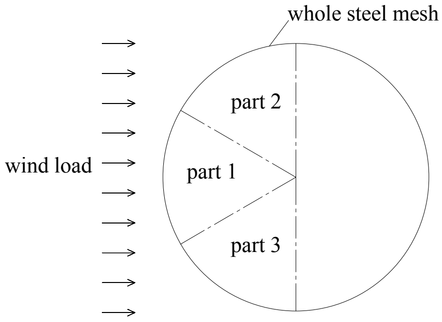

Fig. 4 Wind load calculation diagram

3.5 Calculation results analysis

3.5.1 The first condition: calculation of whole model

(1) Deformation

The maximum displacement is 59.07mm, as shown in Figure 5

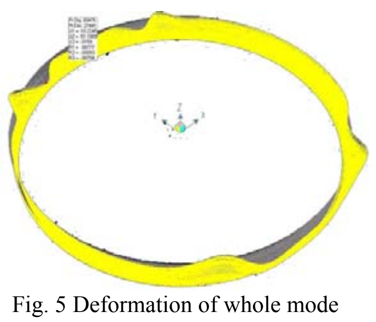

Fig. 5 Deformation of whole mode

TABLE III
CALCULATION RESULTS SUMMARY (HORIZONTAL REINFORCEMENT)

Maximum axial force (N)	Larger axial force (N)	Corresponding reinforcement stress (N/mm^2)	Corresponding pull of tie wire (N/each root)
11139.5		22.7 (□460)	928.2 (□192)
	8552.1		712.7 (□192)
	8135.6		677.9 (□192)
	6339.2		528.2 (□192)
	5559.5		463.2 (□192)
	5256.3		438.0 (□192)
	4588.5		382.4 (□192)

Note: from the analysis results, bending moment and shear force of bearing are small and have little effect to whole structure, so they are not listed in Table 3.

(2)Part of the calculation results

Results are summarized in Table 3.

(3)Analysis:

The results show that deformation is tiny when steel meshes maintain as an overall structure, at the same time, the stress caused by vertical bending moment and tension of bottom tie wire are both in the safe range. However, axial forces of lap reinforcement in adjacent steel mesh (in the range of 4600~8500N) have exceeded the ultimate bearing capacity of "4 bound connections" (4230N). Hence, tie wires are ruptured; single mesh loses lateral connection and turns into monolithic status as the destruction of overall structure. As to single mesh, there are two possible working state, the first, one side is destroyed while other is still intact; the second, both sides are destroyed.

3.5.2 The second condition: single steel mesh (one side is destroyed while other is intact)

(1) Deformation

The maximum displacement is 1776.8mm, which has greatly exceeded lateral limits, as shown in Figure 6.

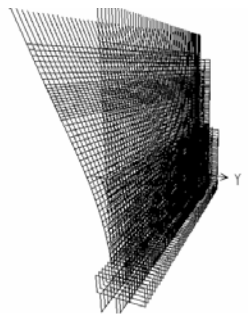

Fig. 6 Deformation of Single steel mesh
(one side is destroyed while other is intact)

(2) Part of the calculation results

In the bearing position, the greatest bending moment is 4.62e5 N*mm and the greatest shear force is 317N, corresponding maximum steel stress is 301 N/mm^2, reinforcement does not yield.

(3) Bound force of mesh bottom

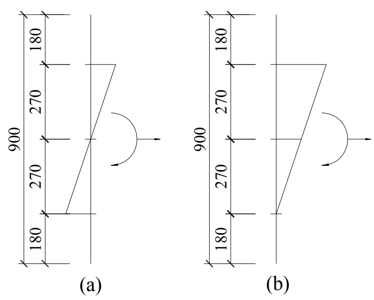

Fig. 7 Calculation diagram of bound force (Units: mm)

There are two types of deformation, as shown in Figure 7.

Φ (a): mesh rotates around the middle lashing point.

Maximum bound force is:

N_1=317.3/3+462194/ (270+270) =961.6N.

⊘ (b): mesh rotates around the bottom lashing point.

Maximum bound force is

N_2=317.3/3+462194×2/ (270+4×270) =790.4N.

So, the greatest bound force can be considered as 961.6N.

(4) Analysis

Tie wires in one lateral side have not broken, reinforcements are also not yield, but the maximum bound force of mesh bottom is 961.6N, which has exceeded the ultimate bearing capacity of tie wire(192*4=768N). Moreover, the maximum displacement is 1776.8mm, such a large deformation will cause eccentric load which may aggravate the instability of structure.

3.5.3 The third condition: single steel mesh (both sides are destroyed)

(1) Deformation

The maximum displacement is 3004.9mm, which has greatly exceeded lateral limits, as shown in Figure 8.

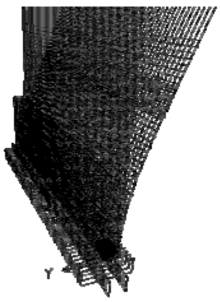

Fig. 8 Deformation of Single steel mesh (both sides are destroyed)

(2) Part of the calculation results

In the bearing position, the greatest bending moment is 5.75e5 N*mm and the greatest shear force is 213N, corresponding maximum steel stress is 374 N/mm^2, reinforcements does not yield too.

(3) Bound force of mesh bottom (as shown in Figure 7).

① (a): N_1=231.08/3+574791/(270+270)=1141.5N.

② (b): N_2=231.08/3+574791×2/(270+4270)=928.6N.

So, the greatest bound force can be considered as 1141.5N.

(4) Analysis

Though reinforcements are not yield, the maximum bound force of mesh bottom is 1141.46N, which has greatly exceeded the ultimate bearing capacity of tie wire(192*4=768N). In addition, the maximum displacement is 1776.8mm, such a large deformation will cause eccentric load which may aggravate the instability of structure.

IV. Conclusions

(1) Under the action of 6-level wind, tie wires of adjacent meshes will be ruptured; single mesh loses lateral connection and turns into monolithic status as the destruction of overall structure. As to single mesh, no matter one side is destroyed while other is intact, or both sides are destroyed, its bottom connection will be destroyed, which may lead to an overall collapse.

(2) From the mode of failure, the reinforcements are not yield even though whole structure is collapsed. So, according to yielding criterion of the boundary edge fiber, stability factor should be greater than 1.7, structure should be inclined to safety. But structure displays obviously instability. This show that reliable measure should be developed to ensure the connection strengthen of adjacent mesh, otherwise overall structure is unsafe.

(3) Wind load is the main cause of structure instability, the project's basic wind pressure uses the data of on-site measure (0.117kN/m^2), which is much smaller than the value of Chinese criteria (for example, value of Shanghai region is 0.55kN/m^2). So, the structure instability will be further aggravated if criteria data is adopted.

(4) Above analysis is based on an ideal state of steel mesh: ① mesh is installed without aberration and kept vertical; ②other eccentric load (such as builder climbing, etc) is not included; ③ the dynamic impact of wind load is not taken into account; ④as to tie wire, loosening under the influence of pulse power is also not considered (experiment shows that the bearing capacity of loose wire will significantly reduced). As the actual situation is more complicated and adverse, security of steel mesh is worse.

(5) In the stage of design, to enhance the stability during installation, height of steel mesh should be reduced (suitable for 5~6m); at the bottom, more reliable connections (such as increasing the quantity of bound, etc.) should be taken to prevent bearing failure.

(6) In the stage of installation, verticality of single steel mesh should be carefully controlled to reduce the additional eccentric loads. At the same time, reliable lateral connection should be set to prevent lateral overturning.

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