Finite Element Analysis of Overhead Pipeline Truss Bridge under Thermal Fluid Loads

Guantang Lin¹, Si Huang²*, Qifeng Niu³, Zhengnan Xu⁴, Cong Zhang⁵ and Yinghong Chen⁶
¹,⁶Guangdong Institute of Special Equipment Inspection and Research Zhuhai Branch, Zhuhai, China, 519002
²,³,⁴,⁵School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, China, 510641
*Corresponding author

Abstract: The subject used in this study is an overhead pipeline truss bridge which sits in a chemical industrial park. The overhead pipeline truss bridge is a part of a pipeline system consisting of 10 sets of columns, 4 layers of pipe racks and 27 pipelines that transports flowing media under various temperature and pressure conditions. An integrated ANSYS finite element model was built considering the factors such as gravity, medium temperature, and flow load, etc. The results of the distributions of displacement, axial force, shear force, bending moment and stress of the overhead pipeline truss bridge were calculated. The primary stress and secondary stress were checked to judge the reliability of the overhead pipeline truss bridge. It concluded that the computation model and calculation used in this study is feasible and effective. The feature in this paper is to explore a practical method and to provide a solid technological foundation for the safety operation and assessment of overhead pipeline truss bridge.

Keywords: overhead pipeline truss bridge; thermal fluid loads; finite element analysis.

1. Introduction
The overhead pipelines in the chemical industry park are generally several or even dozens of concentratedly laid on the pipe gallery to transport chemical raw materials and finished products under various temperature, pressure and flow conditions, and the span of the pipe gallery is large, and it will encounter deep trenches, roads, rivers and other areas with complex engineering geology. In order to avoid the influence of complex terrain on the pipeline, the pipe gallery is generally provided with a spanning device such as a pipeline truss bridge. In recent years, relevant investigations have carried out research work on pipeline truss bridges. Istiting and Thier [1] performed a survey of criteria in the design of pipeline systems for the viewpoint of safety. They concluded that static and dynamic loads acting on the pipeline system owing to thermal stresses called for an analysis of the forces and moments as well as for possibilities of compensation. Ralph Alan Dusseau [2] studied the wind load response of two suspension pipeline bridges. Yanqiang Liu et al [3] analyzed effects of possible loads such as earthquake, temperature change, wind-force, weight of truss and pipe, pressure test and cross-sectional type and size of the truss on structural safety. Urdea M [4] studied about truss deformations to find the best form for trusses using Solidworks software. However, the above mentioned investigations for overhead pipeline truss bridge were mainly based on some commonly design principles, and lacked sophisticated and integrated
computational methods and assessments. In this work, an overhead pipeline truss bridge in a chemical industrial park in South China was selected as the research object. By taking into account the factors such as gravity, medium temperature, flow forces on the pipeline, the ANSYS finite element model was established systematically to perform the thermal fluid loads calculation. The article aims to explore a practical method for the safety assessment of a complex overhead pipeline truss bridge, and to provide a solid technological foundation for the safety operation of the overhead pipeline truss bridge.

2. Finite Element Model

2.1. Geometric Model

By simplifying the actual parameters, the geometric model of the overhead pipeline truss bridge is shown in Figures 1 and 2, for longitudinal and transverse directions respectively. The horizontal layout of the steel frame is shown in Figure 3. The pipe gallery had 10 sets of columns and 4 layers of pipe racks, the first layer of pipe rack had 5 pipes, the second layer had 3, the third layer had 3, the fourth layer had 16 and a total of 27 pipes. The pipe number is shown in Figure 2.

![Figure 1. Longitudinal schematic of the model.](image1)

(a) Pipe racks 3 and 4  
(b) The rest pipe racks  

![Figure 2. Longitudinal schematic of the model.](image2)

![Figure 3. Horizontal layout of steel frame.](image3)

2.2. Element Type in Finite Element Method (FEM)

According to the layout of the overhead pipeline truss bridge shown in Figure 1, 2 and 3, the ANSYS Parametric Design Language (APDL) finite element model of ANSYS was established. Pipe racks and steel frame were modelled by using beam elements (Beam 189) and pipes modelled by using pipe elements (Pipe 289) [5-8]. Table 1 shows the specific data of pipe rack, steel frame and pipe elements, where B is the sectional length of the beam, H is the sectional height, D is the outer diameter of the...
pipe, $\delta$ is the thickness of the pipe, $T_1$ is the thickness of the steel frame web, and $T_2$ is the thickness of the steel frame wing.

2.3. Material Properties

The material constants used in the finite element model are shown in Table 2. The integrated overhead pipeline FEM model of ANSYS was built by the material of the structure, the element type and the element section size, which included 29780 elements and 58834 nodes. Figure 4 shows the FEM grids of the overhead pipeline truss bridge.

**Table 1.** Finite element parameters.

| Structural part     | Element type | Section size (mm) | Material type |
|---------------------|--------------|-------------------|---------------|
| Pipe rack           | Pipe column  | $B = 600, \ H = 500$ | Concrete K475 |
|                     | Beam189      | $B = 500, \ H = 300$ |               |
|                     |              | $B = 950, \ H = 500$ |               |
|                     |              | $B = 700, \ H = 500$ |               |
| Beam of Pipe rack   | Pipe289      | $D = 89, \ \delta = 3.5$ | 1020 steel    |
|                     |              | $D = 108, \ \delta = 3.5$ |               |
|                     |              | $D = 159, \ \delta = 3.5$ |               |
|                     |              | $D = 219, \ \delta = 4$ |               |
|                     |              | $D = 273, \ \delta = 4.5$ |               |
|                     |              | $D = 325, \ \delta = 5$ |               |
|                     |              | $D = 377, \ \delta = 5$ |               |
|                     |              | $D = 426, \ \delta = 5$ |               |
|                     |              | $D = 529, \ \delta = 6$ |               |
| Pipeline (Number)   | String beam and vertical rod | $B = 350, \ H = 350, \ T_1 = 12, \ T_2 = 19$ | Grade 50     |
|                     | Steel frame Abdominal rod  | $B = 300, \ H = 300, \ T_1 = 10, \ T_2 = 15$ |               |
| Steel frame         | Horizontal support | $B = 70, \ H = 5$ |               |
|                     | Steel frame beam  | $B = 294, \ H = 200$ |               |

**Table 2.** Material parameters.

| Material       | Elastic modulus $E$ (MPa) | Poisson’s ratio $\mu$ | Density $\rho$ (kg/m$^3$) | Thermal expansion coefficient $\alpha$ (°C$^{-1}$) | Part               |
|----------------|--------------------------|-----------------------|----------------------------|---------------------------------------------------|--------------------|
| Concrete K475  | $3.15 \times 10^4$       | 0.2                   | 2450                       | $1.0 \times 10^{-5}$                              | Pipe rack          |
| 1020 steel     | $2.1 \times 10^4$        | 0.3                   | 7800                       | $1.2 \times 10^{-5}$                              | Pipeline           |

**Figure 4.** Finite element mesh of overhead pipeline truss bridge.
2.4. Transport Media and Operational Parameters

According to the actual situation on site, the transported media and their physical properties and operating conditions are shown in Table 3.

Table 3. Medium parameters in pipeline.

| Media                        | Pipeline (Number) | Density \( \rho \) (kg/m\(^3\)) | Viscosity \( \nu \) \((10^{-6} m^2/s)\) | Flow \( Q \) (m\(^3\)/h) | Pressure \( p \) (MPa) | Temperature \( T \) (℃) | Thermal Conductivity \( k \) (W/m·K) |
|------------------------------|------------------|----------------------------------|------------------------------------------|--------------------------|------------------------|-------------------------|-----------------------------------|
| Superheated steam            | 13               | 15.4                             | 14.8                                     | 721                      | 1.25                   | 194                     | 0.07                             |
| Oily sewage                  | 15               | 850                              | 8                                        | 591,378                   | 0.8                    | 25                      | 0.5                              |
| Naphtha                     | 3, 11, 23        | 653, 760, 760                    | 8                                        | 196                      | 40                     | 0.11, 0.14, 0.11            |
| Aviation kerosene            | 24               | 780                              | 3.5                                      | 196                      | 40                     | 0.12                     |
| Condensate Hydrocracking oil | 8                | 800                              | 8                                        | 842                      | 40                     | 0.14                     |
| Diesel oil                  | 27               | 832                              | 13.2                                     | 196                      | 40                     | 0.12                     |
| Wax oil                     | 14, 26           | 855, 955                         | 8                                        | 842,842                  | 40                     | 0.12, 0.12                |
| Fuel oil                    | 2                | 877                              | 8                                        | 378,991                  | 80                     | 0.11, 0.12                |
| Crude oil                   | 1, 12            | 959, 950                         | 8                                        | 1468,2267                | 40                     | 0.14, 0.14                |
| Solvent oil                 | 22               | 970                              | 2.74                                     | 87                       | 40                     | 0.12                     |
| Distillate                  | 6                | 1000                             | 8                                        | 378                      | 80                     | 0.11                     |
| 92#gasoline                 | 17               | 746                              | 8                                        | 842                      | 40                     | 0.15                     |
| 95# gasoline                | 18               | 746                              | 8                                        | 291                      | 40                     | 0.15                     |
| Light aromatic hydrocarbon  | 4                | 730                              | 8                                        | 1142                     | 40                     | 0.14                     |
| Aromatic hydrocarbon        | 5                | 890                              | 8                                        | 1142                     | 80                     | 0.14                     |
| Heavy aromatic hydrocarbon  | 16               | 1000                             | 30                                       | 591                      | 80                     | 0.12                     |
| Xylem mixture               | 25               | 860                              | 8                                        | 196                      | 40                     | 0.13                     |
| Toluene                     | 20               | 866                              | 8                                        | 86                       | 80                     | 0.13                     |
| Benzene                     | 21               | 879                              | 8                                        | 86                       | 80                     | 0.16                     |
| Aromatic products           | 10               | 680                              | 8                                        | 196                      | 80                     | 0.14                     |
| Non-aromatic products       | 9                | 800                              | 8                                        | 56                       | 40                     | 0.12                     |

3. Load and Constraints

The load in FEM computation mainly included the gravity, medium temperature, flowing forces acted on the pipeline. Fixed constraints were imposed on both ends of the pipes and the bottoms of the columns in the calculation.

3.1. Thermal Load

The pipeline is expanded and compressed due to the difference between the flowing medium temperature and the local temperature while installation. Therefore, the thermal and structure options were chosen together in FEM calculation [9-11]. Tables 2 and 3 show the material expansion coefficient, media operating temperature and thermal conductivity for FEM thermal load.

3.2. Flow Load

The force acted by the flowing medium on the pipeline mainly includes the resistance along the path caused by the viscous flow and the force generated by the 90° elbow [12]. The resistance along the pipe path is written as:

\[
F_x = (p_1 - p_2)A = \frac{\lambda l}{d} \frac{\rho v^2}{2} A
\]  

(1)

Where \( \lambda \) is resistance coefficient dependent on Reynolds number, \( l \) is the length of the pipe, \( d \) is the inner diameter of the pipe, \( v \) is the flow velocity, \( A \) is the cross-sectional area of the pipe, \( P_1 \) is
pipe inlet pressure, $P_1$ is pipe outlet pressure, as shown in Figure 5. The force on the 90° elbow is expressed in equation (2). The direction and the position of force are shown in Figure 6.

\[ F_x = (p_1 + \rho v^2)A, \quad F_y = (p_2 + \rho v^2)A \]  

\[ (2) \]

**Figure 5.** Resistance along the pipe path.  
**Figure 6.** Force on the 90° elbow.

4. Calculation Results and Analysis  
The analysis and judge for calculation results mainly focused on the overall displacement and stress distribution of the overhead pipeline truss bridge. The horizontal support structure focuses on the maximum value of the bending moment and shear force, while the column focuses on the maximum axial force and its corresponding position.

4.1. Displacement Distribution  
Figure 7 and 8 are respectively X-direction and Y-direction calculated displacements of the overhead pipeline truss bridge. From the figures, the maximum X-direction displacement (13.48 mm) appeared in the pipe 15 conveying oily water between the rack 2 and the rack 3. The maximum Y-displacement (14.01 mm) occurred between 5 and 6 horizontally arranged in the steel frame shown in Figure 3. In addition, the general structure under static action needs to meet the $\delta/L \leq 1/900 = 1.11 \times 10^{-3}$, where $\delta$ represents the maximum deflection, $L$ represents the length of the truss bridge, that is, $\delta/L = 0.01401/39 = 3.59 \times 10^{-4} \leq 1.11 \times 10^{-3}$, it is known that the truss bridge satisfies the stiffness requirement under the combined force.

**Figure 7.** X-direction displacement distribution.  
**Figure 8.** Y-direction displacement distribution.
4.2. Von Mises Stress Distribution
Figure 9 shows the calculated Von Mises stress distribution of the overhead pipeline truss bridge. From the figure, the maximum stress (149 MPa) appeared in the pipe 15 conveying oily water in contact with the fourth-layer beam of the rack 6. Since the inner diameter of the pipe was small, the medium temperature and the flow velocity were high, the stress in the pipe was higher than others.

Figure 9. Von Mises Stress distribution.

4.3. Axial Force Distribution
Figure 10 shows the column axial force distributions of the overhead pipeline truss bridge. From the figure, the bottoms of the two highest columns in the overhead pipeline truss bridge, the racks 3 and 4, the largest axial force is 2230 KN, cross section is 600×600 mm, and the compressive strength value is 6.2 N·mm⁻², which is much less than the design value of Concrete K475 concrete compressive strength 16.3 N·mm⁻²[13].

Figure 10. Column axial force distribution.

4.4. Shear Force Distribution
Figure 11 is a shear force distribution of the overhead pipeline truss bridge. It can be seen from the figure that the maximum shear force on the beam was 315.78 kN, which appeared at the fourth-layer beam of the rack 4 connecting with the pipeline 12. The maximum shear force on the pipe was 41.91 kN, which occurred on the pipe 12 conveying crude oil. This means that the maximum shear force of the beam and the pipe occurs at the higher rack on the transition path between high and low in the truss bridge.
4.5. Bending Moment Distribution

Figure 12 shows the calculated bending moment distributions of the overhead pipeline truss bridge. It can be seen from the figure that the maximum bending moment of the rack beam was 238.89 kN·m, which appeared at the junction of the pipeline 8 and the second-layer beam of the rack 5, The maximum bending moment of the pipeline was 129.63 kN·m, which appeared at the pipeline 12 conveying crude oil. This means that the maximum bending moment of the beam and the pipeline also appears on the lower rack on the transition path from high to low in the compensator.

5. Pipe Strength Check

According to the technical standards of industry [14-15], the primary stress $\sigma_1$, the secondary stress $\sigma_2$ and total stress $\sigma_t$ of the pipeline are required to satisfy the following conditions.

$$\sigma_1 \leq 0.75\sigma_s, \quad \sigma_2 \leq 0.72\sigma_s, \quad \sigma_t \leq \sigma_s$$  \hspace{1cm} (3)

Where $\sigma_s$ is the yield strength of the pipe, $\sigma_1$ is caused by gravity and other loads, $\sigma_2$ is caused by thermal deformation only, $\sigma_t$ is caused by all loads and thermal deformation. It can be seen in Table 4 that the calculated stress of the overhead pipeline truss bridge satisfies the above condition (3). This indicates that the overhead pipeline truss bridge is reliable in service.
Table 4. Strength check.

| Stress type | Allowable stress(MPa) | Max calculated value(MPa) | Whether the strength met requirement |
|-------------|-----------------------|---------------------------|-------------------------------------|
| $\sigma_1$  | 221.3                 | 125                       | Yes                                 |
| $\sigma_2$  | 212.4                 | 122                       | Yes                                 |
| $\sigma_t$  | 433.7                 | 247                       | Yes                                 |

6. Conclusion
(1) The maximum displacement of the overhead pipeline truss bridge is in the middle of the steel frame. Through the $\delta / L$ stiffness check, the stiffness of the pipeline truss bridge meets the design requirements.
(2) The bottom of the highest column in the overhead pipeline truss bridge bears the maximum axial force. The maximum shear and bending moments of the rack beam occur in the rack beam from the high to low transition of the rack. The maximum shear force and bending moment of the pipeline appear at the junction of the higher rack between the high and low rack.
(3) In the entire overhead pipeline truss bridge, the maximum stress occurs at the contacting position of the pipe with a smaller inner diameter, higher medium temperature and flow velocity with the beam. By the strength check, the present studied model meets the design requirements.

References
[1] Isting C and Their B 1977. Chemical-Engineering and Safety in Design of Pipeline Systems in Chemical-Plant. Chemie Ingenieur Technik, vol 7, p 528-535.
[2] Dusseau R A 1990. Wind analysis of pipeline suspension bridges. Journal of Wind Engineering and Industrial Aerodynamics, p 927-936.
[3] Liu Y Q and Rui S H I 2017. Analysis of Environmental Effect and Optimization on Truss Overhead Crossing Structure Design of Oil and Gas Transmission Pipeline. DEStech Transactions on Engineering and Technology Research 3rd/amma.
[4] Urdea M 2018. Static linear analysis for trusses structure for supporting pipes. IOP Conference Series: Materials Science and Engineering, Vol 399, p 012051.IOP Publishing.
[5] Zhang X and Du Q 2011. Research on heat-solid coupled numerical simulation of engine exhaust pipe based on ANSYS. 2011 International Conference on Electric Information and Control Engineering. p 6070-6073. IEEE.
[6] Deng C, Wan X, Zhang Z, et al 2012. Numerical Modelling and Analysis of Infrared Testing in Delaminations of Pressure pipes Using ANSYS. 2012 Symposium on Photonics and Optoelectronics. p 1-4. IEEE.
[7] Jinmei T. 2008. Comparison of Beam Element and Shell Element in Analyzing Inherent Vibration of Structures. Nuclear Power Engineering, vol 1, p 50-52.
[8] Feng L, Deguo W, Lu L, et al 2010. Simulation of APDL-Based Super-High Pressure Compressor Pipeline System Vibration Control. 2010 International Conference on Digital Manufacturing & Automation,vol 2, p 366-369. IEEE.
[9] Bellet M, Jaouen O and Poitrault I 2005. An ALE-FEM approach to the thermomechanics of solidification processes with the prediction of pipe shrinkage. International Journal of Numerical Methods for Heat & Fluid Flow, vol 2, p 120-142.
[10] Krushinski V I 1974. Calculation of L-Shaped Pipelines to Provide for Compensation of Thermal Elongations, Taking into Account Friction in Sliding Supports. Energomashinostroenie, p 20-22.
[11] Shevchenko Y U N, Babeshko M E and Gololobov V I 1993. Calculation Procedure of Axisymmetrical Thermoelastoplastic Stress Strained State of Compensating Elements of Thermoinsulated Pipelines. Problemy Prochnosti (Russia), vol 8, p 87-93.
[12] Yamaguchi H 2008. Engineering fluid mechanics Vol. 85. Springer Science & Business Media.
[13] ACI Committee 2005. Building code requirements for structural concrete (ACI 318-05) and commentary (ACI 318R-05). American Concrete Institute.

[14] American Society of Mechanical Engineers 2009. Pipeline Transportation System for Liquid Hydrocarbons and Other Liquids: ASME Code for Pressure Piping, B31.4 American Society of Mechanical Engineers.

[15] American Society of Mechanical Engineers 2018. Gas Transmission and Distribution Piping Systems: ASME Code for Pressure Piping, B31.8. American Society of Mechanical Engineers.