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Study of Semi-Rigid Joints Effect on Global Stiffness of Space Steel Structure Based on Monitoring Data

Cheng Yuan[1], Wei Lu[1], Jun Teng[1] and Weihua Hu[1]
[1]Harbin Institute of Technology, Shenzhen, 518071, China
email: Chengyuan@hit.stu.edu.cn, Lu.wei@hit.edu.cn, tengj@hit.edu.cn, huweihua@hit.edu.cn

ABSTRACT: In conventional structural design and analysis of space steel structures, joints are typically idealized as either perfectly hinged or fully rigid connections. However, actual joint behavior deviates significantly from these idealized assumptions, with joint stiffness exhibiting semi-rigid characteristics that critically affect global structural performance. This discrepancy between simplified joint models and real-world conditions leads to substantial errors in predicting structural stiffness through numerical simulations. This paper presents a novel methodology integrating structure health monitoring with refined finite element (FE) modeling to quantify the semi-rigid joints effect on global stiffness space steel structure. The joint stiffness parameters are inversely identified through stress and deformation monitoring data using Bayesian inference techniques; A multi-scale FE model incorporating semi-rigid joint behavior is developed through component-level validation; The stiffness evolution mechanism is rigorously validated against full-scale monitoring data from the Shenzhen Nanshan Science-Technology Innovation Center's space frame during its service period. Key findings demonstrate that joint flexibility reduces global stiffness by 18-22% compared to rigid-joint assumptions, with stiffness degradation rates showing strong correlation to stress redistribution patterns. The proposed joint-characterization framework provides a physics-based approach for tracking long-term stiffness evolution in space steel structures, offering significant improvements over conventional design methods in both accuracy and predictive capability.

KEY WORDS: Semi-Rigid Joints, Space Steel Structure Stiffness, Structure Health Monitoring.

1 INTRODUCTION

Structural connection joints are the critical components of space steel structures, which are subject to complex forces and are sensitive to defects. The mechanical properties and stress of the joints not only affect the safety of the joint itself but also have an influence on the stress distribution and deformation of the overall structure.

In China's "Code for Design of Steel Structures", it is stipulated that the truss and the space frame should be analyzed according to the hinge connection, while the single-layer space shell should be processed according to the rigid connection [[1]]. However, more and more engineering projects show that ideally hinged joints often have certain rigidity, while ideal rigid joints also have certain flexibility. The research work of Grogan [[2]] and Wheelar [[3]] show that neither completely rigid nor hinged joint exist in reality. The uncertainty of joint stiffness is mainly caused by the following factors. The structure discontinuity of the structure. The bolts are not tightened between the nodes and members connected by bolts, which leads to insufficient stiffness of the joints. The structure has defects. Due to geometric defects such as dislocation or slippage between components and nodes during installation, or physical defects such as cracks, the stiffness of joints decreases. The structure is deteriorating in its service life. The structure is affected by fatigue and corrosion, which leads to the deterioration of the joints.

The research on joint stiffness has received extensive attention in recent years. The "specification for structural steel structure" edited by AISC pointed out that the connection joints of steel structures should be divided into three situations, namely ideal simple connection, fully restrained moment connections and partially restrained moment connections [[4]]. The Eurocode 3 also has a description similar to that in the AISC code, which divides the joints into three types: rigid, semi-rigid and hinged [[5]]. Although the Eurocode 3 and AISC code mention the general classification standards of three types of joints, there is no relevant description on how the stiffness of semi-rigid joints is determined, and how the attenuation of joint stiffness will affect the overall structure's stiffness.

The existing research mainly contains three methods for calculating the value of joint stiffness which are numerical simulation, laboratory specimen test and mathematical statistics. Liu [[6]] used Abaqus to model the pin joints to analyze their stiffness, and Cao [[7]] used Ansys to model the network frame joints to analyze their stiffness. The numerical simulation of joint stiffness is convenient, but the premise assumptions of material properties and connection methods used in finite element simulation may be different from the actual states of joints in reality. Liao [[8]] obtained the load-displacement curve of the joint by making a scaled model in the laboratory for loading, and then calculated the joint stiffness data. However, the scaled model cannot reflect the actual stress state of the full-scale structure. Frangopol [[9]] obtained the probability distribution curve of the deterioration degree of the connection joints of steel truss bridges by analyzing the test report data of a large number of bridges by means of mathematical statistics. However, there are certain regional differences in this method. The degree of corrosion and deterioration of steel structures under different climatic environments is significantly different. The probability

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distribution cannot determine the change trend of joint stiffness of a specific structure.

In conclusion, there are premise assumptions for numerical simulation, differences between the scaled model and the full-scale structure for laboratory test, and regional differences in mathematical statistical analysis. In this paper, the field monitoring data of structural stress and displacement are obtained based on Nanshan Science and Technology Innovation Center monitoring project through stress sensors and prisms. The stiffness of the joints of steel truss are obtained by inversion of the monitoring data of stress and displacement by the deflection method. The updated joint stiffness is substituted into the finite element model. The influence of the joint stiffness on the overall stiffness of the structure is studied through the updated finite element model.

2 JOINT STIFFNESS CALCULATION

2.1 Joint Stiffness Calculation Method

The stiffness of the joints is calculated by the deflection method. The total beam deflection comprises two constituent parts: one part is the deflection caused by the ideal elastic deflection of the beam; the second part is the displacement of a point on the beam caused by the deformation of the joint, as shown in Fig. 1.

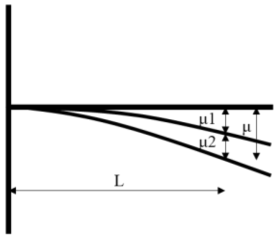


Figure 1. General view of deflection method

μ_1 is the deflection of the ideal elastic deflection line of the beam at this point. μ_2 is the displacement at this point due to the deformation of the joint. μ is the real deflection of the point, and L is the distance from the point to the joint. μ can be calculated as:

$$\mu_1 + \mu_2 = \mu \quad (1)$$

The angle of downward deflection at the joint can be calculated as:

$$\theta_r = \frac{\mu}{L} = (\mu_1 + \mu_2)/L \quad (2)$$

In this project, μ is obtained by prism observation in field monitoring, and μ_1 is obtained by linear elastic simulation with finite element software. The joint stiffness K_j can be calculated as:

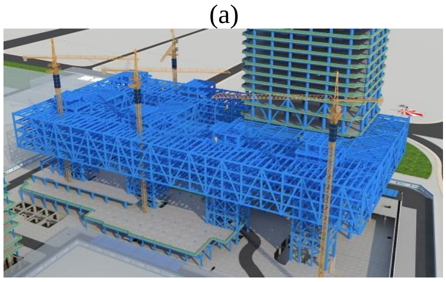
$$K_j = M / \frac{(\mu - \mu_1)}{L} \quad (3)$$

M in formula (3) is the bending moment of the joint, which is obtained by finite element simulation.

2.2 Joint Stiffness calculation Results

Shenzhen Nanshan Science and Technology Innovation Center includes seven towers (A1-A7) and a huge podium surrounding the towers. The steel structure of the podium is located on the 7th to 11th floors, as shown in Fig. 2. The steel structure of the podium consists of a large span truss and a cantilevered truss structure.

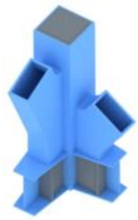
(a)



(b)

Figure 2. Shenzhen Nanshan science and Technology Innovation Center. (a) completed structure rendering and (b) construction process

The typical joint of the large span steel truss of the podium of Nanshan Science and Technology Center is shown on Fig. 3. The joints and the members are connected by welding.



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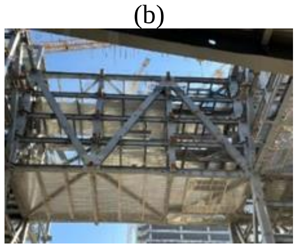

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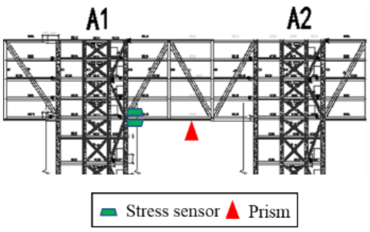
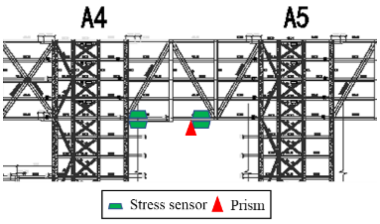
Figure 3. Typical joint (a) Joint model. (b) diagonal web is being welded to the bottom joint. (c) The installation of truss between A4-A5 is completed.

In this project, the vibrating wire stress sensor is used to monitor the stress of the structure. The prism and electronic total station are used to monitor the displacement of the structure. In this paper, the displacement monitoring data is used to calculate the real stiffness of the structure, and the stress monitoring data is used to verify the validity of the finite element model after updating the joint stiffness.

The stress sensors and prisms have been installed on the large-span trusses connecting the core tubes A1, A2, A4, and A5, and the stress and displacement of the structure at the current construction stage have been monitored. The positions of stress sensors and prisms are shown in Fig. 4.



(a)



(b)

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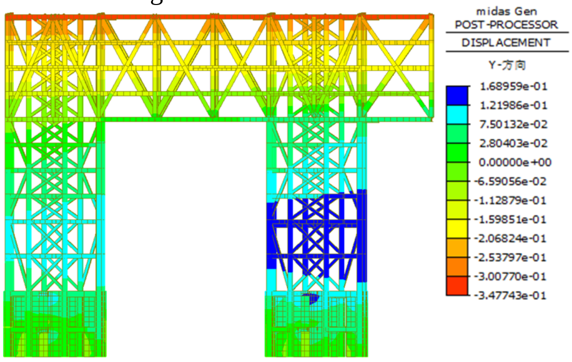
Figure 4. Stress sensors and Prisms on truss. (a) truss between A1-A2, (b) truss between A4-A5 and (c) sensor installation diagram (in red box)

The finite element analysis of the current phase of the structure was performed using Midas Gen, and the truss members were modeled as beam elements. The mid-span deflection of the lower chord and the bending moment at both ends of the lower chord of the large-span truss between A4 and A5 are calculated only considering the self-weight load of the structure. The vertical displacement diagram and the stress diagram of the truss is shown in Fig. 5.



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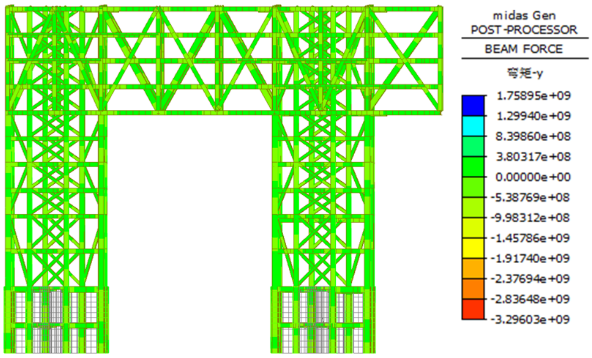

(b)

Figure 5. Finite element simulation. (a) vertical displacement diagram. (b) Stress diagram.

The deflection μ_1 produced by ideal elasticity at the mid-span of the large-span truss (the triangle mark in the figure) is extracted from Fig. 5. The bending moments M of joint L and R are extracted from Fig. 6 (b). and midspan deflection μ of the truss between A4-A5 is 6 mm based on field monitoring data. The stiffness of joint L and R are calculated based on formula (3) and results are shown in Table 1.

Table 1. Joint stiffness results.

	Joint L	Joint R	Calculation method
μ (mm)	6		Monitoring data
μ_1 (mm)	2.6		Finite element
θ_r (rad)	$3.96*10^{-4}$	$3.96*10^{-4}$	Formula (2)
M (kN*m)	110.7	80.7	Finite element
K_j (kN*m/rad)	$4.94*10^5$	$3.60*10^5$	Formula (3)

3 EFFECT ON GLOBAL STIFFNESS

3.1 Updating of Joint Stiffness

According to the calculation results shown in Table 1, the previous rigid joint is updated with the stiffness $4.94*10^5$

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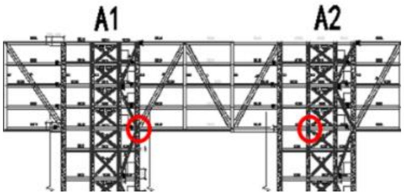
kN*m/rad, $3.60*10^5$ kN*m/rad and $4.27*10^5$ kN*m/rad (average of joint L and joint R).

The bottom joints of the web members of the trusses connecting A1-A2, A1-A4 and A4-A5 are updated with new stiffness. The joint locations for the updated stiffness are shown in Fig. 6. Twelve joints of the web members have undergone stiffness updates. The method of joint stiffness updating is to replace the original rigid joints in structural model with spring beams with springs at both ends.



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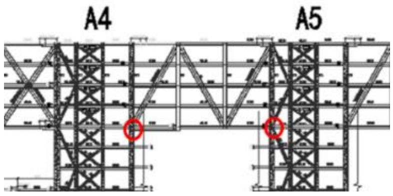

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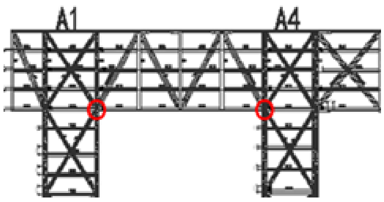


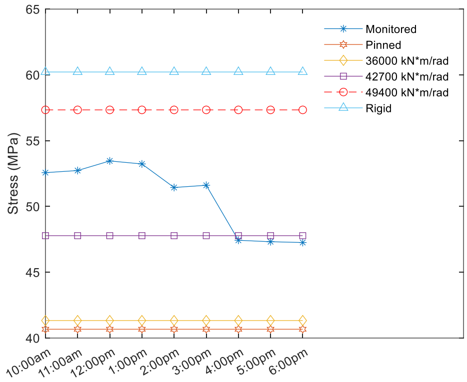
(c)

Figure 6. Positions of joints for stiffness updating. (a) truss A1-A2. (b) truss A4-A5. (c) trussA1-A4

3.2 *Finite Element Model Vertification*

Five cases of joint stiffness cases are being simulated using finite element method which are rigid, $4.94*10^5$ kN*m/rad, $4.27*10^5$ kN*m/rad, $3.60*10^5$ kN*m/rad and pinned. The load on the structure only considers the self-weight load. The remaining cases are simulated in the same way. The structural stress obtained from the finite element simulation is compared with the structural stress obtained from the field monitoring data to verify the model with updated joint stiffness.

The joint stress at the same position of the monitoring point is extracted from the structural stress diagram for comparison. The location of measuring points for structural monitoring is shown in Fig. 4. The comparison between the simulation results and the monitoring data is shown in Fig. 7.



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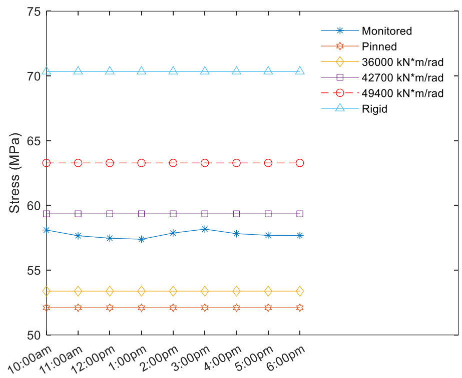

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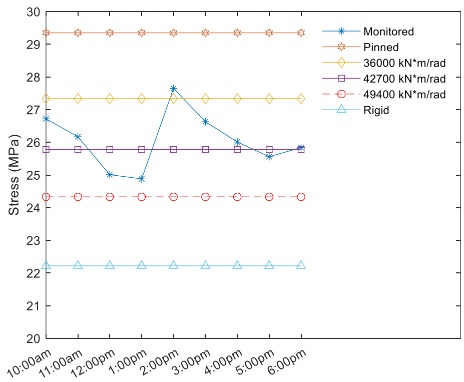

(c)

Figure 7. Comparison between the simulation results and the monitoring data. (a) stress at end of truss between A1-A2, (b) stress at end of truss between truss A4-A5 and (c) stress at midspan of truss A4-A5.

The following conclusions can be drawn from the comparison between monitoring data and simulated data in Fig. 7. The stress data simulated by the semi-rigid joint model are closer to the structural monitoring data. Among them, the model stress value after joint stiffness update with the average stiffness of joint L and joint is the closest to the monitoring data. This indicates that this stiffness is the closest approximation to the true stiffness of the bottom joint of the web member of the truss.

3.3 *Effect of Joint Stiffness on Global Stiffness of Structure*

According to the results in 3.2, it is considered that $4.27*10^5$ kN*m/rad is the true stiffness of the bottom joint of the web member of the large-span truss. Apply different vertical

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uniform loads to the structure and draw the load-deflection curves of the large-span trusses A4-A5. The load-deflection curves of the ideal rigid joint, semi-rigid joint and ideal hinged joint model are compared in Fig. 8.

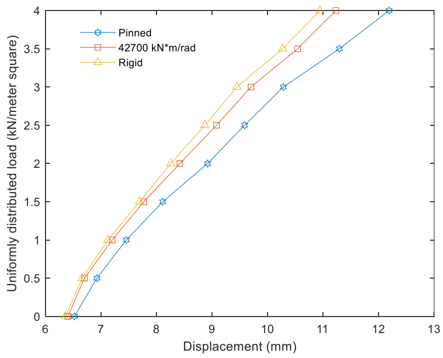
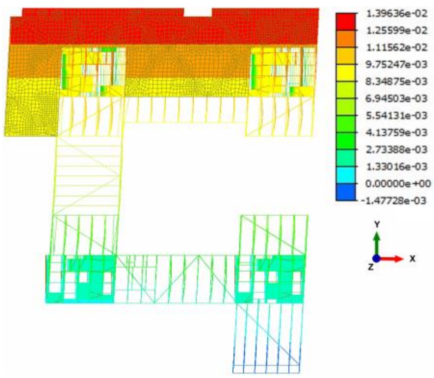


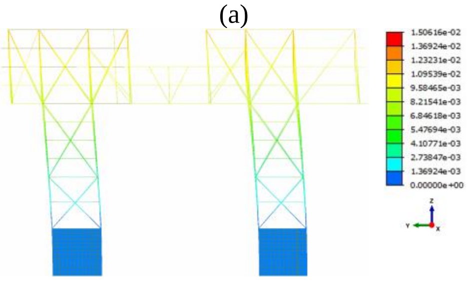
Figure 8. A4-A5 truss load-displacement curve.

It can be seen from Fig. 9. that the vertical stiffness of the ideal rigid joint model is the largest, followed by the semi-rigid joint model, and the vertical stiffness of the hinge joint model is the smallest. The truss load-deflection curves of the ideal rigid joint, semi-rigid joint and ideal hinged joint model are linearly fitted, and the slope of the load-deflection curve is the vertical stiffness of the A4-A5 large-span truss. The calculation results show that the vertical stiffness of the semi-rigid joint truss is 5.4% lower than the rigid joint model and 13.4% higher than the pinned joint model.

The mode shapes of the structure has been simulated to analysis the joint effect on global stiffness of the structure. The first-order mode is translation in the x-direction (parallel to the A1-A2 direction), the second-order mode is translation in the y-direction (parallel to the A1-A4 direction), and the third-order mode is translation in the x-direction. The mode shapes of the structure show in Figure 9. The frequency of the structure with different joint stiffness is shown in Table 2.



(a)



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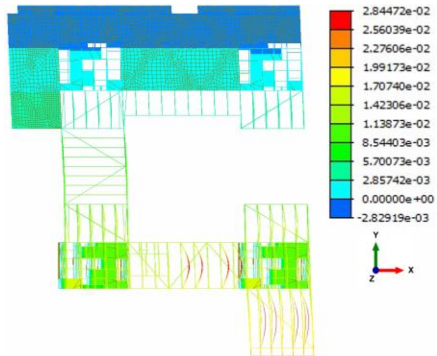

(c)

Figure 5. Mode shapes of the structure. (a) first order, (b) second order and (c) third order

Table 2. Frequency of the structure.

Mode order	Frequency (Hz)		
	Rigid joints	Semi-Rigid Joints	Pinned Joints
1	1.3369	1.2366	1.2256
2	1.4826	1.2823	1.2358
3	1.7203	1.3199	1.2286

The mode shape simulation result shows that natural frequency of the structure decreases as the joint stiffness reduces. Since frequency can reflect the stiffness of the structure, the result also tells that joint stiffness can strongly affect the global stiffness of the structure.

4 CONCLUSION

The effect of joint stiffness on overall structure is studied in this paper. The influence of the stiffness characteristics of the joints at the end of the truss and the mid-span of the truss are different. For the joints at the end of the truss, the stress of the semi-rigid joint is larger than that of the hinged joint and smaller than that of the rigid joint; For the joints at the midspan of the truss, the stress of the semi-rigid joint is smaller than that of the hinged joint and greater than that of the rigid joint. The semi-rigid joint is most consistent with the field monitoring data. The load-deflection curve of the large-span truss is simulated, and the results show that the vertical stiffness of the truss of the semi-rigid joint model is 5.4% lower than that of the ideal rigid joint model and 13.4% higher than the hinged joint model. The conclusions of this paper can be references for other steel structure analysis.

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