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# Research on Importance Evaluation Method of Semi-rigid Space Frame Structure Members Based on Structural Strain Energy

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## ABSTRACT

Traditional design of space grid structures typically relies on the assumption of pinned joints. While this simplification streamlines the evaluation of member importance, it fails to account for the semi-rigid behavior of actual connections. This discrepancy often leads to inaccuracies in structural analysis and member importance ranking, introducing potential risks of misjudgment. To overcome these limitations, this study develops a more refined evaluation framework. First, a high-fidelity finite element model (FEM) of a semi-rigid space grid was established, incorporating joint rotational stiffness. Members were simulated using segmented beam elements, and the model's accuracy was rigorously validated against experimental data. Subsequently, a comprehensive evaluation index was proposed based on structural strain energy, which integrates multiple internal force components, including axial force, bending moment, and shear force. Finally, the proposed method was applied to a regular square pyramid space grid to compare member importance rankings against traditional methods. The underlying internal force redistribution mechanisms were analyzed by selecting representative members with significant ranking discrepancies. The results indicate that while both methods show consistent trends for most members, substantial differences exist in critical regions, such as the top chords. Mechanism analysis reveals that the traditional pinned-joint model, by neglecting moment transfer, results in simplified load paths and stress concentrations, thereby overestimating the importance of specific members. In contrast, the semi-rigid model accurately reflects the diversified load-transfer mechanisms facilitated by joint moments. This study confirms that joint semi-rigidity significantly influences the assessment of member importance. The proposed method effectively identifies and corrects misjudgments caused by the pinned-joint assumption, providing a more reliable theoretical basis for identifying critical components and optimizing maintenance strategies, particularly for complex space structures requiring high assessment precision.

## KEYWORDS

Space grid structures; Semi-rigid joints; Member importance; Strain energy.

## 1. INTRODUCTION

In traditional design and analysis of space grid structures, the Technical Specification for Space Grid Structures (JGJ 7—2010)[1] stipulates that joints in space trusses are assumed to be pinned.

Comprehensive reviews of existing literature[2-5] indicate that connection types widely used in engineering practice are neither ideally pinned nor fully rigid; instead, their mechanical behavior generally exhibits semi-rigid characteristics with rotational capacity. Subsequent studies[6-8] have further revealed a significant correlation between the stiffness parameters of such connections and the global stability and bearing capacity of the structure. However, it is important to note that the simplified joint assumptions prevalent in current design codes neglect bending stiffness, which often fails to accurately reflect the actual restraint conditions at the connections. This leads to an inability to account for the impact of secondary internal forces induced by bending moments, resulting in computational deviations. The discrepancy between these theoretical models and engineering reality can critically influence structural safety assessments, prompting extensive research[9-11] into stiffness correction methods for finite element models.

Space grid structures typically consist of a large number of components, making comprehensive inspection prohibitively expensive and time-consuming. Due to their high degree of static indeterminacy and inherent structural robustness, the influence of individual members on global performance varies. Evaluating member importance allows for the effective identification of critical components essential to safety, thereby reducing the risk of structural failure triggered by damage to key areas.

Traditional importance evaluation methods for space trusses, predicated on the pinned-joint assumption, primarily determine criticality through changes in global structural stiffness or member stress ratios before and after component removal. Cai et al.[12] conducted a sensitivity analysis on orthogonal square pyramid space grids, using member removal as the sensitivity parameter and stress ratio as the structural response to calculate importance coefficients. Zhou et al.[13] utilized the variation in stress ratios following member removal to quantify component importance for a stadium roof in Quanzhou, providing a basis for structural appraisal and reinforcement. Liu et al.[14] proposed a stiffness-based assessment method and performed case studies on planar truss and frame systems. Luo et al.[15] established a system of criteria and calculation methods for member importance derived from global stiffness and the capacity of components to resist external loads.

However, the aforementioned methods face limitations when applied to semi-rigid grid systems. The moment transfer effects inherent in semi-rigid connections alter the internal force distribution, subjecting members to a combined action of axial force, bending moment, and shear force. Under these conditions, relying solely on stiffness matrix eigenvalues or stress ratio parameters fails to fully characterize a component's true contribution to the complex mechanical state—the former struggles to capture the redistribution of secondary internal forces induced by joint rotational stiffness, while the latter overlooks the impact of bending strain energy on global performance. Consequently, the traditional evaluation framework fails to theoretically represent the comprehensive mechanical characteristics of the members, potentially leading to the misidentification of critical components in practical applications.

Based on this, the present study first establishes a mechanical model for semi-rigid space grids that effectively accounts for member instability and joint stiffness. Subsequently, structural strain energy is proposed as the core index for evaluating member importance. The advantage of this method lies in its ability to integrate the work performed by multiple internal force components, including axial force, bending moment, and shear force, fundamentally overcoming the limitations of traditional single-parameter evaluations.

## 2. ESTABLISHMENT AND VALIDATION OF THE SEMI-RIGID SPACE GRID MODEL

### 2.1. Mechanical Model of Semi-Rigid Joints in Space Grids

In the modeling of semi-rigid joints for space grids, node bodies are established at both ends of the member. Semi-rigidity is implemented in ABAQUS by assigning connector elements (K1, K2) at the joint interfaces, as illustrated in Fig. 1. The length of the node body is denoted as $\lambda l$ . In practical space grid structures, the dimensions of the node body typically range from 4% to 8% of the total member length; a median value of 6% is adopted for the modeling in this study. Given a center-to-center distance l between two nodes, the clear length of the member, accounting for the node body dimensions, is expressed as $(1-2\lambda)\ l$.

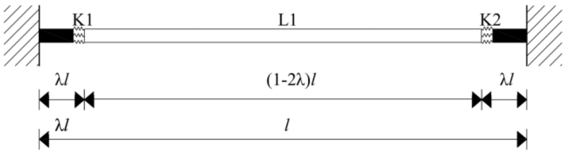


**Fig. 1** Mechanical model of members with semi-rigid joints

In this study, the U-Joint from the ABAQUS connector library is selected for simulation. The U-Joint element provides full kinematic constraints for the translational degrees of freedom (U1, U2, U3) and the rotational degree of freedom UR2 between the connected nodes, thereby restricting displacements in the X, Y, and Z directions as well as rotation about the Y-axis. Meanwhile, the rotational degrees of freedom UR1 and UR3 are retained, allowing relative rotation between the nodes about the X and Z axes. Under this configuration, the three translational stiffnesses of the node and the torsional stiffness of the member are considered infinite, while the bending stiffness of the member in two orthogonal directions can be explicitly defined. A local coordinate system is generated for each member, where the y-direction is defined along the longitudinal axis of the member. The connectors at both ends of each member are oriented based on this local coordinate system. As illustrated in Fig. 2, this modeling approach comprehensively captures the spatial mechanical characteristics of the joints.

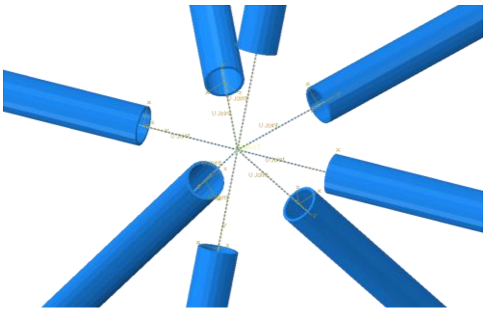

**Fig. 2** Schematic diagram of semi-rigid joint connections

In this study, the bending stiffness of the joints is determined by introducing the normalized bending stiffness. The expression for the normalized bending stiffness is as follows:

$$k_b = K_b \frac{(1-2\lambda)l}{EI} \tag{1}$$

In this expression, $K_b$ represents the bending stiffness of the joint, $(1-2\lambda)\ l$ is the actual length of the member, and $EI/[(1-2\lambda)l]$ denotes the flexural rigidity of the member. Consequently, the normalized bending stiffness is defined as the ratio of the joint's bending stiffness to the linear stiffness of the member.

**Table 1** Ranges of values for different joint types [16]

| Joint Type | Range of Values $k_b$ |
|---|---|
| Welded Hollow Spherical Joint | $k_b > 30$ |
| Bolted Ribbed Cylindrical Joint | $10 < k_b < 30$ |
| Bolted Cylindrical Joint | $1 < k_b < 10$ |
| Bolt-ball Joint | $0.1 < k_b < 1$ |

## 2.2. Element Selection in Space Grid Analysis

For members in space grids, the results of simulation analyses vary significantly depending on the element type selected. In engineering design, it is conventionally assumed that members only sustain axial forces with pinned end conditions, leading to the adoption of a two-force member (truss element) mechanical model. However, because truss elements possess only axial stiffness, they cannot account for member buckling, which leads to an overestimation of the overall structural stability. In contrast, beam elements can simultaneously account for axial force, bending moment, shear force, and torsional effects. This allows for a more accurate simulation of the actual mechanical behavior of space grids under complex loading conditions, offering higher engineering applicability and analytical reliability.

In this study, the beam element (B31) in ABAQUS is employed for simulation. Each member is divided into 10 segments, which effectively controls the computational workload while ensuring calculation accuracy.

## 2.3. Validation of the Semi-Rigid Space Grid Mechanical Model

The space grid model in reference [17] is a 3.6×3.6 m orthogonal square pyramid space grid with a height of 0.849 m and a grid size of 1.2 m, simply supported along its perimeter. All members have a length of 1.2 m and consist of $\phi 48\times 3.5$ steel tubes. The bolt-ball joints have a diameter of 110 mm, and the material is Q345 steel. Loads were applied uniformly to the four nodes at the center of the top chord (Node P). To ensure synchronous loading, a distribution beam loading system was employed (Fig. 3). Experimental results indicated that when the total load reached 721.3 kN, the first batch of members exhibited significant buckling, after which the load dropped abruptly and deflection increased sharply.

ABAQUS finite element simulation was performed based on the loading and boundary conditions of the experimental grid. The joints were modeled as bolt-ball joints with a normalized bending stiffness $k_b = 0.5$. The grid members utilized B31 beam elements discretized into 10 segments. The Arc-Length method (Riks) was used for the full-process analysis of the grid to realistically capture nonlinear behavior, structural limit points, and post-buckling responses. An initial geometric imperfection was introduced based on 1% of the first-order buckling mode from the eigenvalue buckling analysis [18].

Fig. 4 presents the load-deflection curve at the mid-span throughout the process from loading to failure, and Fig. 5 illustrates the failure mode of the semi-rigid space grid. Comparative analysis shows that due to the inability of nodes to transfer moments, the pinned-joint model exhibits lower global stiffness in the initial loading stage. In the ultimate stage, it overestimates the bearing capacity by ignoring the axial-bending coupling of members, causing the load-displacement curve to deviate from experimental results. In contrast, the semi-rigid model established in this paper accurately predicts the ultimate bearing capacity. The critical load calculated via the semi-rigid model is 698.2 kN, with an error of only 3.3% compared to the experimental value. The mid-span displacement shows a larger error of 31.6%, which is attributed to the installation tightness issues inherent in bolt-ball joints. The initial stiffness of the experimental load-displacement curve is lower than both the ideal pinned and semi-rigid models. This is likely due to small initial gaps at connection sites, bolt slippage, or the tightening process between components during early loading—factors that introduce additional local deformations not accounted for in the ideal FE model.

These results fully validate the rationality of the semi-rigid model and reveal the systematic errors of the traditional pinned-joint assumption in structural stiffness and stability analysis.

In summary, the nonlinear analysis method for space grid structures constructed in this paper—based on semi-rigid joint models and multi-segment beam element discretization—can accurately predict ultimate bearing capacity and simulate the mechanical response from initial loading to failure. This method provides reliable theoretical support and analytical means for the study of nonlinear behavior in space grid structures.

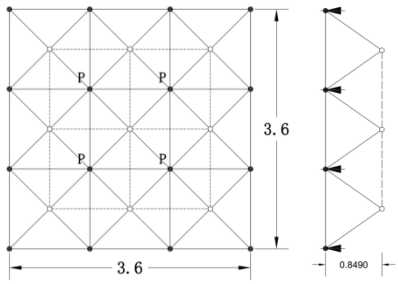


Fig. 3 Space grid model

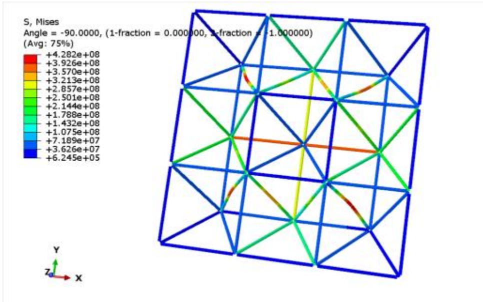


**Fig. 5** Failure modes of the calculation models

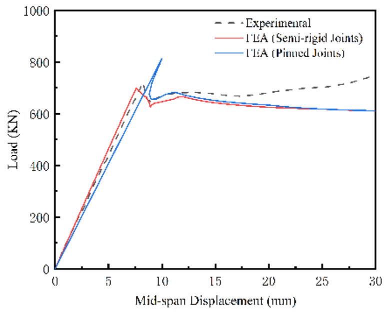


**Fig. 4** Load-displacement curves of the calculation models

## 3. CLASSIFICATION METHODS FOR MEMBER IMPORTANCE IN SPACE GRIDS

### 3.1. Theoretical Basis and Necessity Analysis of the Strain Energy Method

The importance coefficient of a component is typically defined as the degree of impact on a specific global structural performance index following the removal of that component [19][20].

Previous studies evaluating the importance of space grid members were mostly based on pinned-joint models dominated by axial forces, using only changes in axial stress as the evaluation index. However, in actual space grids, members simultaneously sustain bending moments and shear forces. The semi-rigid characteristics of the joints significantly influence local stress and global internal force distribution; therefore, such models may deviate from the actual importance of members in real structures.

Taking the space grid model shown in Fig. 3 as an example, a mechanical analysis was conducted by varying its joint stiffness to study the influence of joint stiffness on the axial forces, bending moments, and shear forces within the grid. The calculation results show that the maximum axial force, bending moment, and shear force all occur in the bottom chord members. As seen in Fig. 6, Fig. 7, and Fig. 8, parametric finite element analysis reveals that joint stiffness has a significant impact on the internal force distribution of the grid members. As joint stiffness increases, the capacity of the joints to transfer moments is enhanced, and the bending moments and shear forces show a clear increasing trend. Meanwhile, the change in axial forces within the grid members is not significant. Relying solely on axial force indicators fails to capture the impact of joint stiffness variations on the true mechanical state of the members. Therefore, there is an urgent need for an evaluation index that can comprehensively represent the coupling effects of axial force, bending moment, and joint stiffness.

Indicators based on strain energy, due to their clear physical meaning and sensitivity to compound loading, can serve as a rational metric for reflecting the actual importance of members in space grid structures.

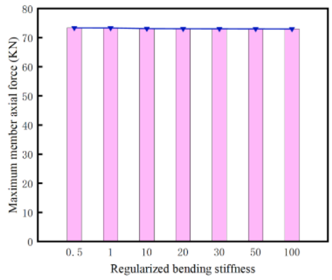


**Fig. 6** Variation of axial force with $k_b$

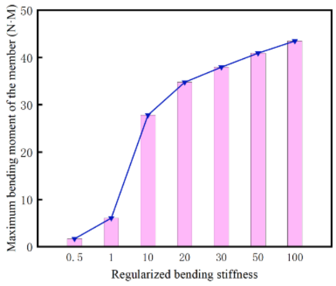


**Fig. 7** Variation of bending moment with $k_b$

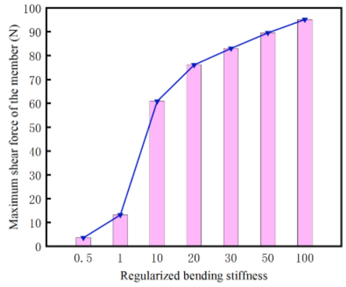


**Fig. 8** Variation of shear force with $k_b$

The member importance evaluation method based on strain energy can comprehensively account for multiple internal force factors, such as axial force, bending moment, and shear force, thereby providing a more thorough reflection of the actual contribution of each member to the overall structural stiffness and deformation coordination. Compared to methods relying solely on axial force as an evaluation indicator, this approach is better suited to revealing the degree of a member's influence on structural performance under complex loading states—particularly under non-ideal conditions such as semi-rigid joint characteristics and initial imperfections. Consequently, adopting strain energy as an evaluation indicator offers higher physical rationality and engineering applicability.

## 3.2. Theoretical Calculation Method for Total Strain Energy

Assumptions used in the analysis: (1) In the evaluation of member importance within the space grid, the stiffness of the failed member is reduced to 1/1000 of its original value [21]. Following component failure, internal force redistribution occurs within the grid. (2) The form of load application remains unchanged before and after member removal. The applied external loads consist of standard load combinations during the structure's service life, and the loading method is static, neglecting the effects of dynamic characteristics. (3) The structure is assumed to be a conservative system, where the work done by external loads is entirely converted into the internal strain energy of the structure, with no energy dissipation occurring throughout the loading process.

The work done by external loads is fully stored within the structure and converted into structural strain energy. The structural strain energy is equal to the sum of the strain energy of all members, namely:

$$W_{ext} = U_{sys} = \sum U_k \tag{2}$$

In this study, the total strain energy of the structure is obtained by direct extraction from the final analysis step in ABAQUS. First, the total strain energy of the intact structure under loading is calculated; subsequently, a single member is artificially "removed" to calculate the resulting total strain energy of the structure [22].

The member importance coefficient is defined as:

$$I_k = 1 - \frac{U_0}{U_k} \tag{3}$$

# 4. MEMBER IMPORTANCE EVALUATION OF SPACE GRIDS BASED ON STRAIN ENERGY

## 4.1. Case Study of the Semi-Rigid Model

### 4.1.1. Case Study Information

ABAQUS was employed to analyze an orthogonal square pyramid space grid with a span of $26.4\mathrm{m}\times 39.6\mathrm{m}$, a height of 2.2 m, and multi-point perimeter supports (see Fig. 9). The length of the web members is 3.207 m. The top chord layer consists of 12 grids in the long-span direction and 8 grids in the short-span direction, with a grid size of $3.3\times 3.3\mathrm{m}$ for both top and bottom chord layers. Q235 circular steel tubes were utilized. The load combination was set as 1.3×Dead Load + 1.5×Live Load, with a roof dead load of $0.7\mathrm{KN/m^2}$ and a live load of $0.5\mathrm{KN/m^2}$ [23]. The uniformly distributed loads were converted into equivalent concentrated loads acting on the top chord nodes based on their tributary areas.

The cross-sections of the space grid members were optimized using the spatial structure analysis and design software MSTCAD under the full-stress design criterion. The cross-sections for the top chords, web members, and bottom chords were standardized separately: the top chords use $\phi 114\times 4$, the bottom chords use $\phi 88.5\times 4$, and the web members use $\phi 75.5\times 3.75$. The specifications and characteristic parameters of the members are presented in Table 2. Members were modeled using B31 beam elements, with each member discretized into 10 elements. Semi-rigid joints were adopted, and bolt-ball joints were simulated by setting the normalized bending stiffness.

Due to the differences in cross-sectional dimensions and lengths among the top chords, bottom chords, and web members, the linear stiffness of the top chords was selected as the basis for calculating Kb, where $K_b = 0.1EI/(1-2\lambda)\ l = 5.93\mathrm{KN{\cdot}m/rad}$.

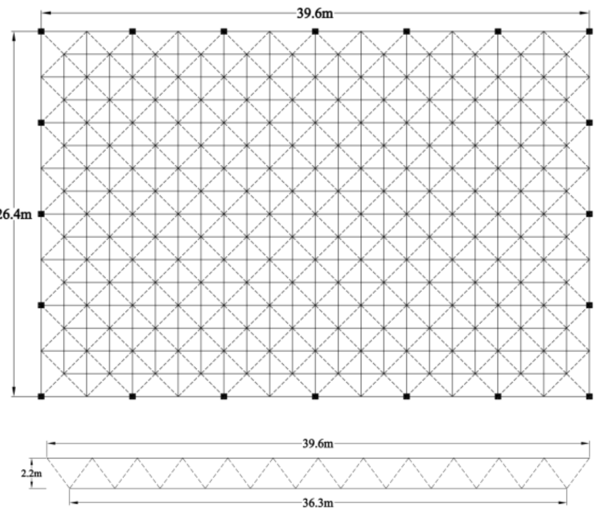


**Fig. 9** Geometry and Boundary Conditions of the Space Grid

**Table 2** Member Characteristic Parameters

| Member Position | Section Type | A/mm$^2$ | I/mm$^4$ | i/mm |
|---|---|---|---|---|
| Web Member | $\phi 75.5\times 3.75$ | 845 | 545433 | 25.4 |
| Bottom Chord | $\phi 88.5\times 4$ | 1062 | 949865 | 29.9 |
| Top Chord | $\phi 114\times 4$ | 1382 | 2093494 | 38.9 |

### 4.1.2. Case Study Results

The total strain energy of the intact space grid under vertical roof loads is 10.74 kJ. By utilizing Python for the secondary development of ABAQUS, the total strain energy after the failure of various grid members was extracted in batches, and the importance coefficients of the members were calculated.

Given that the space grid structure in this case study exhibits biaxial symmetry in terms of geometry, boundary conditions, and loading, a quarter-structure model was adopted for the member importance analysis to improve computational efficiency. By extracting the importance coefficients of each member within the quarter-model range and mapping them according to their symmetrical positions, the importance coefficients for all members of the complete space grid were ultimately obtained. This method significantly reduces the computational scale of the finite element analysis while ensuring the accuracy of the results.

**Table 3** Distribution of Member Importance Coefficients for the Space Grid

| $I_k$ Range | Number of space grid members | | |
|---|---|---|---|
| | Top Chords | Bottom Chords | Web Members |
| [0，1%] | 200 | 100 | 360 |
| [1%，2%] | 12 | 36 | 16 |
| [2%，3%] | 0 | 10 | 8 |
| [3%，4%] | 0 | 12 | 0 |
| [4%，5%] | 0 | 2 | 0 |
| [5%，6%] | 0 | 10 | 0 |
| [6%，7%] | 0 | 2 | 0 |

There are a total of 768 members in the space grid, consisting of 212 top chords, 384 web members, and 172 bottom chords. The specific distribution of the member importance coefficients is shown in Table 3. Among the top chords, 200 members fall within the [0, 1%] range, accounting for approximately 94%, while 12 members are in the [1%, 2%] range. Among the bottom chords, a total of 100 members are in the [0, 1%] range, representing about 58%, and the maximum member importance coefficient falls within the [6%, 7%] range. Among the web members, 360 members are in the [0, 1%] range, accounting for approximately 94%, with 16 and 8 members in the [1%, 2%] and [2%, 3%] ranges, respectively. Based on the analysis above, the maximum value occurs among the bottom chords, at 6.398%.

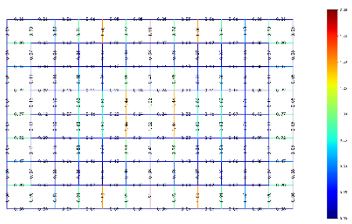

**Fig. 11** Cloud Map of Top Chord Importance Coefficients

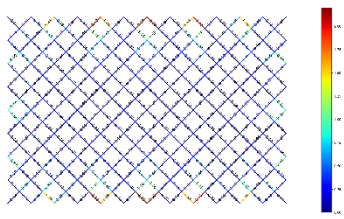

**Fig. 12** Cloud Map of Web Member Importance Coefficients

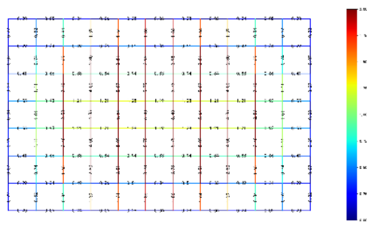

**Fig. 13** Cloud Map of Bottom Chord Importance Coefficients

The importance coefficients of all space grid members were calculated, and the corresponding importance coefficient cloud maps were plotted, as shown in Fig. 11, Fig. 12, and Fig. 13. By observing the cloud map of the top chord members, it can be found that the importance coefficients are higher at the supports and the mid-span. For the web members, the importance coefficients are higher near the supports. For the bottom chords, the importance coefficients are higher at the mid-span.

This distribution occurs because, in a long-span structural system, the bending moment is maximum in the middle section and the shear force is maximum at the supports; the top and bottom chords provide the bending capacity of the structural system, while the web members provide the shear capacity. Furthermore, since the force distribution of the space grid structure is similar to that of a two-way slab, the load is primarily transferred along the short-span direction. Consequently, the supports along the long side provide more structural support than those along the short side, making the members at the long-side supports more important than those at the short-side supports.

## 4.2. Hinged Model Case Study

### 4.2.1. Case Study Information

The model dimensions and member cross-sections are identical to those of the semi-rigidly connected space grid. The only modification is changing the joints to hinged connections, utilizing Truss elements. Each member is divided into a single mesh and subjected solely to axial forces.

### 4.2.2. Case Study Information

The importance coefficients of the members in the hinged space grid were calculated, and the corresponding importance coefficient cloud maps were plotted, as shown in Fig. 14, Fig. 15, and Fig. 16. A preliminary comparison of the cloud maps indicates that the two models exhibit similarities in the spatial distribution patterns of member importance.

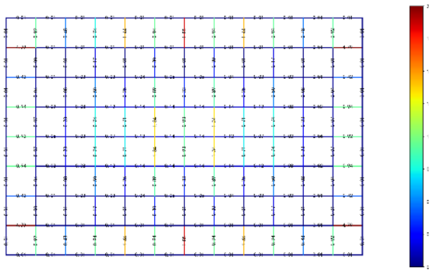

**Fig. 14** Cloud Map of Top Chord Importance Coefficients

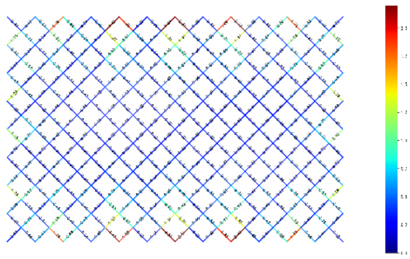

**Fig. 15** Cloud Map of Web Member Importance Coefficients

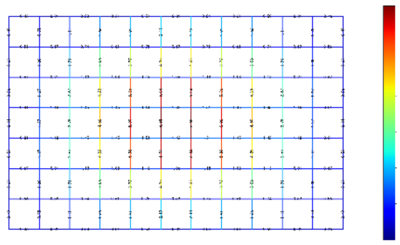

**Fig. 16** Cloud Map of Bottom Chord Importance Coefficients

## 4.3. Comparison of Differences in Member Importance Ranking Between the Two Case Studies

In order to quantitatively evaluate the influence of joint assumptions on the member importance evaluation results, this section performs a systematic comparison of the importance coefficients for key members (members with a cumulative importance frequency greater than 80% are defined as important members [20]) under both the hinged and semi-rigid models. Tables 4, 5, and 6 list the importance rankings and importance coefficients of the top chords, web members, and bottom chords for the hinged and semi-rigid space grids, respectively.

**Table 4** Comparison of Top Chord Importance Ranking Differences

| Rank | Semi-rigid Grid | | Hinged Grid | |
|---|---|---|---|---|
| | ID | Coeff. (%) | ID | Coeff. (%) |
| 1 | U362 | 1.913 | U106 | 4.794 |
| 2 | U139 | 1.496 | U362 | 1.850 |
| 3 | U72 | 1.438 | U139 | 1.436 |
| 4 | U385 | 1.018 | U72 | 1.342 |
| 5 | U373 | 0.979 | U141 | 0.943 |
| 6 | U565 | 0.974 | U581 | 0.942 |
| 7 | U141 | 0.923 | U110 | 0.935 |
| 8 | U581 | 0.921 | U385 | 0.929 |
| 9 | U110 | 0.914 | U565 | 0.922 |
| 10 | U106 | 0.900 | U2 | 0.916 |

**Table 5** Comparison of Web Member Importance Ranking Differences

| Rank | Semi-rigid Grid | | Hinged Grid | |
|---|---|---|---|---|
| | ID | Coeff. (%) | ID | Coeff. (%) |
| 1 | W587 | 2.201 | W587 | 2.507 |
| 2 | W356 | 2.117 | W356 | 2.420 |
| 3 | W115 | 1.577 | W115 | 1.877 |
| 4 | W123 | 1.476 | W123 | 1.782 |
| 5 | W355 | 1.106 | W355 | 1.373 |
| 6 | W586 | 1.049 | W586 | 1.314 |
| 7 | W127 | 0.986 | W127 | 1.283 |
| 8 | W330 | 0.860 | W330 | 1.148 |
| 9 | W122 | 0.828 | W122 | 1.102 |

**Table 6** Comparison of Bottom Chord Importance Ranking Differences

| Rank | Semi-rigid Grid | | Hinged Grid | |
|---|---|---|---|---|
| | ID | Coeff. (%) | ID | Coeff. (%) |
| 1 | L162 | 6.398 | L162 | 6.679 |
| 2 | L383 | 5.752 | L383 | 6.035 |
| 3 | L20 | 5.645 | L20 | 5.902 |
| 4 | L149 | 5.093 | L149 | 5.356 |
| 5 | L311 | 4.347 | L311 | 4.598 |
| 6 | L17 | 3.996 | L17 | 4.255 |
| 7 | L612 | 3.976 | L612 | 4.254 |
| 8 | L371 | 3.507 | L371 | 3.774 |
| 9 | L133 | 2.801 | L133 | 3.065 |
| 10 | L77 | 2.526 | L77 | 2.783 |
| 11 | L318 | 2.405 | L318 | 2.667 |
| 12 | L358 | 1.860 | L358 | 2.134 |
| 13 | L14 | 1.646 | L14 | 1.910 |
| 14 | L584 | 1.635 | L584 | 1.905 |
| 15 | L345 | 1.391 | L345 | 1.660 |
| 16 | L576 | 1.281 | L576 | 1.513 |
| 17 | L74 | 1.212 | L81 | 1.450 |
| 18 | L81 | 1.208 | L74 | 1.449 |
| 19 | L166 | 1.194 | L166 | 1.424 |
| 20 | L90 | 1.109 | L90 | 1.372 |
| 21 | L570 | 1.010 | L570 | 1.268 |

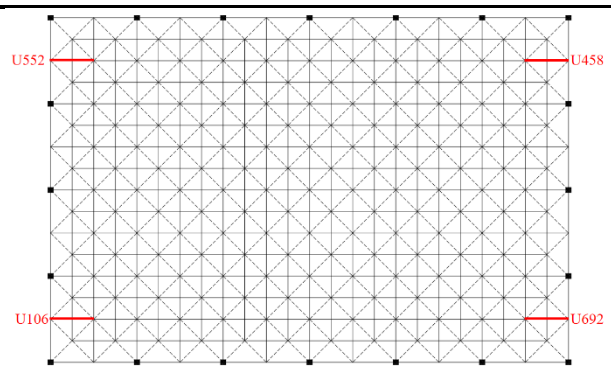


**Fig. 17** Schematic Diagram of the Locations of Members with Importance Anomalies

Through comparative analysis, it is found that although the importance evaluation results of the two models tend to be consistent for most web members and bottom chords, significant discrepancies in conclusions arise for individual top chords due to different joint assumptions. A particularly typical case is the top chord U106, which is identified as a critical component in the hinged model, exhibiting an abnormally high importance coefficient (similarly, the importance coefficients of its symmetrical members in space—U552, U458, and U692—are also anomalous; the locations of these anomalous members are shown in Fig. 17). In contrast, its importance returns to a conventional level in the semi-rigid model. This indicates that ignoring the moment-transfer capability of the joints may lead to a misjudgment of critical components.

To further reveal the mechanism behind these discrepancies, a detailed analysis of the underlying causes is provided below.

# 5. MECHANISM ANALYSIS OF THE DIFFERENCES IN MEMBER IMPORTANCE RANKING

## 5.1. Analysis of Differences Based on Internal Force Response of Adjacent Members

The aforementioned comparative analysis indicates that space grid models based on hinged and semi-rigid assumptions exhibit certain differences in member importance ranking. To further explore the mechanical reasons for these differences, this chapter selects the typical top chord member U106, whose importance coefficient increases significantly in the hinged model, as the research object for in-depth comparative analysis. By analyzing the internal force changes and load redistribution characteristics of adjacent members under the failure scenarios of this specific member in both models, the mechanism of how joint assumptions influence member importance evaluation results is clarified from the perspectives of structural load transfer paths and joint constraint effects.

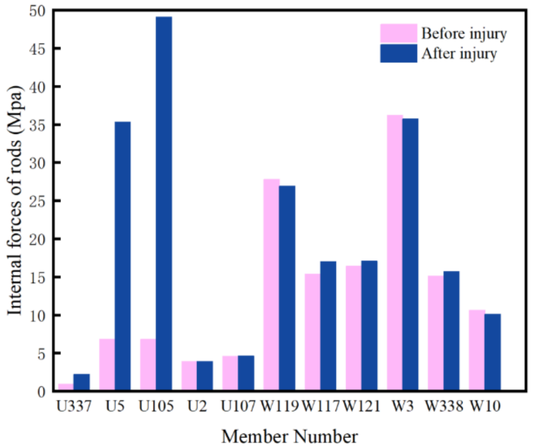


**Fig. 18** Internal Force Changes of Adjacent Members in the Hinged Space Grid After Failure of Member U106

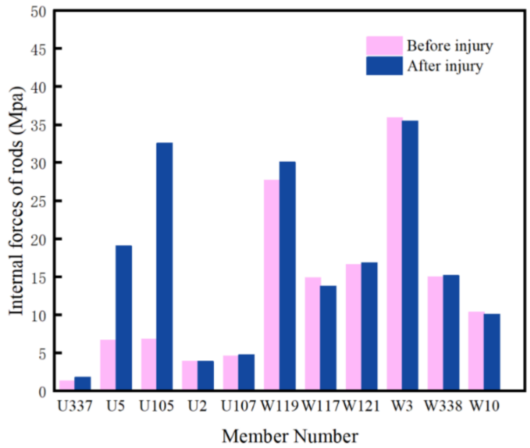


**Fig. 19** Internal Force Changes of Adjacent Members in the Semi-rigid Space Grid After Failure of Member U106

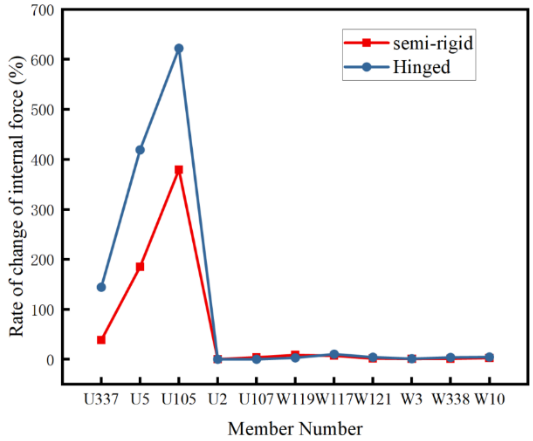


**Fig. 20** Rate of Change in Internal Forces of Adjacent Members After Failure of Member U106

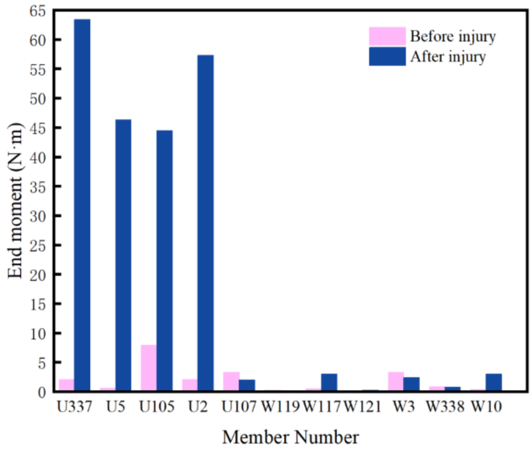


**Fig. 21** Rate of Change in Bending Moments of Adjacent Members After Failure of Member U106

As shown in Fig. 18–Fig. 21, significant differences exist between the hinged and semi-rigid space grid models regarding the internal force transfer and redistribution characteristics of adjacent members after the failure of member U106.

For the hinged model (Fig. 18), since the joints lack the capacity to transfer bending moments, the load redistribution relies primarily on axial force paths among adjacent members. When member U106 fails, the adjacent members must sustain the original load through a significant increase in axial forces. This leads to internal force concentration and a sudden surge in stress, causing the structure to exhibit a "brittle" response dominated by abrupt axial force changes. This reflects the insufficient load redistribution capacity of the structure under the hinged assumption.

In contrast, in the semi-rigid model (Fig. 19), the moment-transfer capacity of the joints is activated, forming a multi-path load transfer mechanism characterized by the synergy of "axial force and bending moment." As seen in Fig. 20, the rate of change in the internal forces of adjacent members in the semi-rigid model is significantly lower than that in the hinged model, indicating a more dispersed load transfer and higher static redundancy and mechanical toughness. Furthermore, Fig. 21 shows that in the semi-rigid model, the end moments of adjacent top chords rise significantly after the failure of U106. The joint moment-sharing mechanism is fully utilized, effectively mitigating the stress concentration caused by local failure.

Consequently, by ignoring the joint moment-transfer effect, the hinged model leads to an overestimation of internal forces in local members, resulting in inflated importance coefficients and potential misjudgments. The semi-rigid space grid model established in this study more accurately reflects the joint constraint effects and load transfer characteristics, making the importance evaluation results more consistent with the actual mechanical state. This model demonstrates higher rationality and applicability for analyzing the member importance of space grid structures, providing a more reliable theoretical basis for the safety assessment and reinforcement decision-making of existing space grids.

### 5.2. Analysis of Differences Based on Displacement Response of Adjacent Nodes

To further reveal the influence of joint semi-rigidity on the global mechanical and deformation characteristics of the space grid structure after the failure of critical members, this section selects typical member failure scenarios to comparatively analyze the differences in displacement response between the hinged and semi-rigid models. By extracting the displacement variation patterns of key nodes throughout the entire loading process, the reasons for the misjudgment of member importance in the hinged model are explored.

Figures 22 and 23 illustrate the spatial displacement response cloud maps for the semi-rigid and hinged models, respectively, following the failure of member U106. As shown in the figures, member U106 is located in the peripheral area of the space grid. After its failure, the displacement at the edge nodes increases significantly in both models, resulting in localized deformation concentration.

To accurately quantify the relative differences in deformation at the edge nodes and further reveal the differences in deformation mechanisms between the hinged and semi-rigid models after critical member failure, this study selects a node adjacent to member U106 (Node 5) as a typical measurement point. The load ratio–displacement relationship curves in the X, Y, and Z directions (Fig. 24, Fig. 25, and Fig. 26) were extracted, and the vertical displacement variation curve of the mid-span node of the space grid (Fig. 27) was plotted.

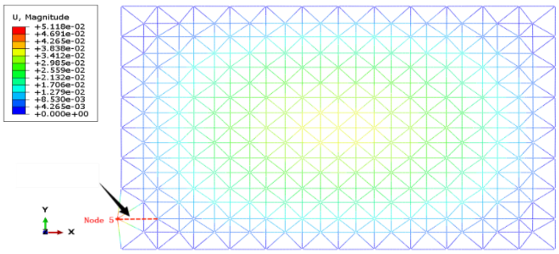


**Fig. 22** Displacement Response Cloud Map of Semi-rigid Model After Failure of Member U106

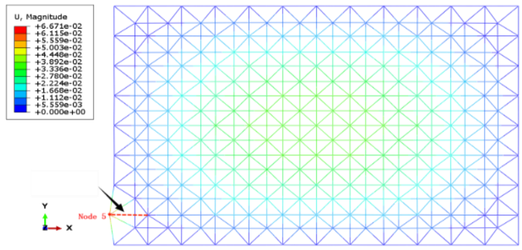


**Fig. 23** Displacement Response Cloud Map of Hinged Model After Failure of Member U106

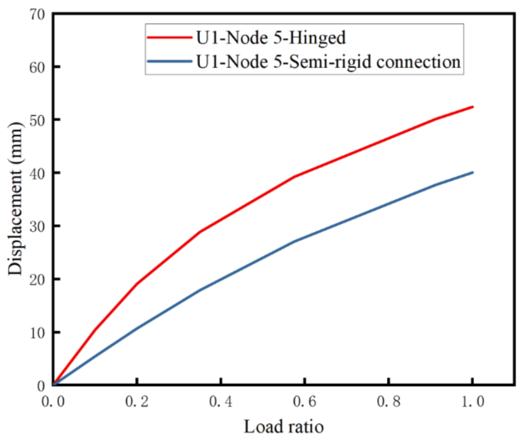


**Fig. 24** Load-Displacement Curve of Node 5 in the X-direction

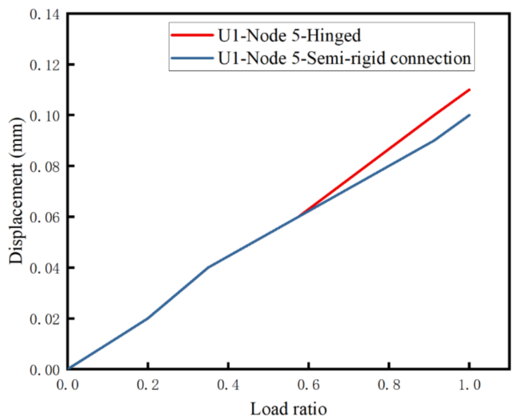


**Fig. 25** Load-Displacement Curve of Node 5 in the Y-direction

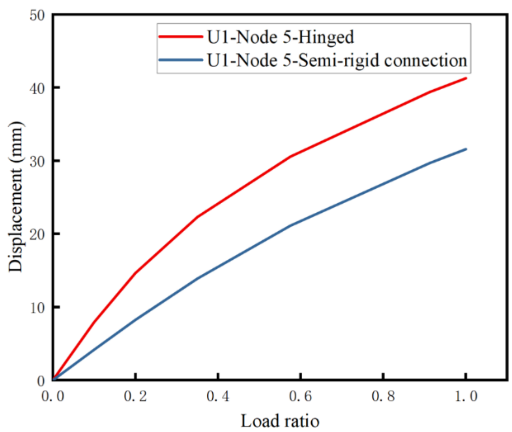


**Fig. 26** Load-Displacement Curve of Node 5 in the Z-direction

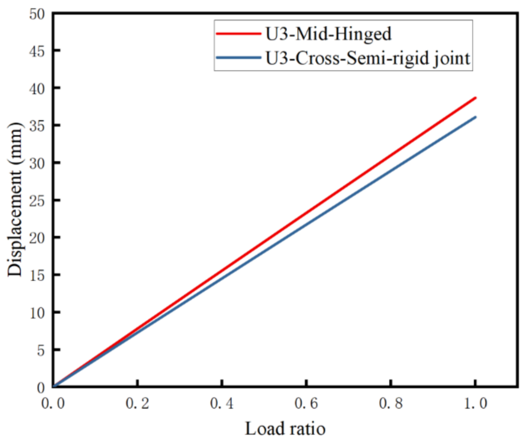


**Fig. 27** Vertical Displacement Curve of the Mid-span Node

As shown in Fig. 27, after the failure of member U106, the displacement difference between the two models at the mid-span node is relatively small, but they exhibit distinct behaviors at the edge nodes. In the hinged model, the displacement of nodes adjacent to the failed member increases significantly, and local deformation is highly concentrated. This indicates that the load-transfer path is weakened due to the reliance on a single axial force transfer mechanism. In contrast, in the semi-rigid model, the inherent stiffness of the joints results in a more gradual local displacement distribution and better overall deformation coordination.

These results demonstrate that by ignoring the bending moment constraint effect of the joints, the hinged model tends to overestimate the importance of adjacent members in the peripheral zones, leading to misjudgments. The semi-rigid model more accurately reflects the force redistribution characteristics of the structure under local damage, thereby preventing erroneous assessments of member importance.

## 6. CONCLUSION

This study investigates the influence of joint semi-rigidity on the evaluation of member importance in space grid structures. By establishing a refined semi-rigid finite element model, proposing a comprehensive evaluation index based on structural strain energy, and systematically comparing the results with those of the traditional hinged model, the following primary conclusions are drawn:

(1) Joint connection assumptions exert a systemic influence on the overall performance of the structure. Validation results indicate that traditional hinged models, by ignoring the moment-transfer capacity of joints, fail to reflect the axial-bending coupling effect in members. Consequently, this systematically overestimates the ultimate bearing capacity of the structure. In contrast, the semi-rigid finite element model established in this paper accurately predicts the ultimate bearing capacity and failure modes, verifying its reliability and applicability as a refined analytical tool.

(2) Strain energy serves as a vital mechanical index for evaluating member importance in semi-rigid space grids. Compared to traditional single-parameter indices based solely on axial force or stiffness, the strain energy index comprehensively captures the energetic contributions of various internal force components, including axial force, bending moment, and shear force. From an energy perspective, it provides a holistic measure of a member's contribution to the global stiffness and stability. Its clear physical meaning and high sensitivity to complex stress states fundamentally address the deficiencies of traditional evaluation methods regarding comprehensiveness and accuracy.

(3) Semi-rigid joint characteristics significantly affect the identification of critical members. The case study comparison shows that while both models maintain consistent importance rankings for most web members and bottom chords, distinct discrepancies exist in the evaluation of certain top chord members. Mechanism analysis reveals that due to the singular load-transfer path in the hinged model, the failure of a local member leads to a violent redistribution of axial forces in adjacent members, thereby systematically overestimating their importance. Conversely, by incorporating the joint moment-transfer effect, the semi-rigid model facilitates a more dispersed load-transfer path, resulting in a smoother internal force redistribution and evaluation results that are more reasonable and consistent with actual mechanical behavior.

(4) The research methodology presented possesses significant value for engineering applications. The findings demonstrate that considering semi-rigid joint characteristics is crucial for identifying critical components in space grid structures. The "Semi-rigid Model—Strain Energy Index" comprehensive evaluation system proposed in this study effectively corrects misjudgments of member importance caused by traditional hinged assumptions. This provides a more reliable theoretical basis and technical support for optimized resource allocation in structural health monitoring, safety assessment, and reinforcement projects.

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