Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Experimental and theoretical study on reticulated shell structure composed of plate members

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Abstract
Challenges in constructing an ideal curved surface with traditional section steel members include unavoidable manufacturing defects and imperfect curve-fitting. Recent investigations indicate that planar steel exhibit flexibility, efficiency, and precision in outline shape fabrication through computerized numerical control cutting machines. These advantages make customized plate members particularly suitable for constructing small or medium-span curved-surface structures. In this study, a novel type of reticulated shell structure composed of built-up plate members has been proposed. First, built-up double-limb plate members are proposed to solve the instability of plates about the weak axis. Second, the rotational performance of plate-type joints is revealed by a four-stage model. Third, the stability of reticulated shell structures is fully investigated by experimental and theoretical means. This research can provide valuable guidance for their design and application.

Keywords: plate member, reticulated shell structure, stability behavior, experiment.

1. Introduction
Reticulated shell structures have developed rapidly and gained popularity over the last decades. Their benefits such as prefabricated members and assembly installation have facilitated the industrialization of spatial structure buildings. Although steel profiles, such as I-section steel, are commonly used as the main structural members, planar steel plates have been shown to be a viable alternative according to recent research. Specifically, planar steel plates have demonstrated potential advantages in efficiency and precision of fabrication, as well as convenience of storage and transportation.

A novel reticulated shell structure composed of plate members has been presented by Ge et al. [1], as shown in Fig. 1. In the reticulated shell structure composed of plate members, the plate members are connected by plate-type joints. The curved-surface outlines of the structure are accurately assembled by the plate members, specifically, double-limb built-up plate members. Plate members have several significant advantages. Above all, the steel plates have good flexibility, efficiency, and precision in outline shape fabrication by computerized numerical control cutting machines. Next, planar plates can be piled up with high space utilization, which is convenient for storage and transportation. Additionally, the simple connection form of plate-type joints ensures a clear node force transmission mechanism. These advantages make the customized plate members very suitable for building small or medium-span curved-surface structures.

When used as structural members, the steel plates exhibit the specific mechanical properties of beam members, which are bearing axial and bending force. However, compared to common beam members, the cross-sections of plate members have a rather smaller size along the minor axis. According to the elastic mechanic theory, the flexural buckling behavior of a beam member is related to the rotational inertia of its cross-section. Due to the limited thickness of the steel plate, a single plate member may occur flexural buckling problems about the minor axis when bearing axial compressive force. Although it is possible to improve the stability of plate members by increasing the cross-sectional area, it may significantly increase the costs and self-weight of the structure. A more reasonable strengthening method is to assemble two single plates into a built-up plate member. These built-up plate members have more optimal cross-sections, with higher material efficiency and better mechanical properties. The built-up plate members are composed of two identical limb plates with short plates as intermediate connectors. All the elements are cut by a laser cutting machine. The limb plates are bolted with intermediate connectors at certain intervals along the length direction. The built-up strengthening method can effectively improve member stability under compressive loads. Furthermore, double-limb built-up members can be altered to multi-limb members for structures requiring stronger members.

The plate-type joint is typically composed of several steel plates (Ge et al. [2]). The central node of a plate-type joint is welded with several steel plates. The plate members are assembled with the central node by bolts and washers. The plate-type joints are designed based on the cross-sections of the built-up plate members. The intermediate connectors at both ends of the members are replaced by the joint plates. This type of joint can effectively transmit the external loads mainly by the deformation of the central nodes and the bolt group. Also, it allows for a simplified construction process, which reduces the overall construction time and cost. Besides, the joint plates can be adjusted to accommodate changes in the dimensions or shape of the structure during the construction process.

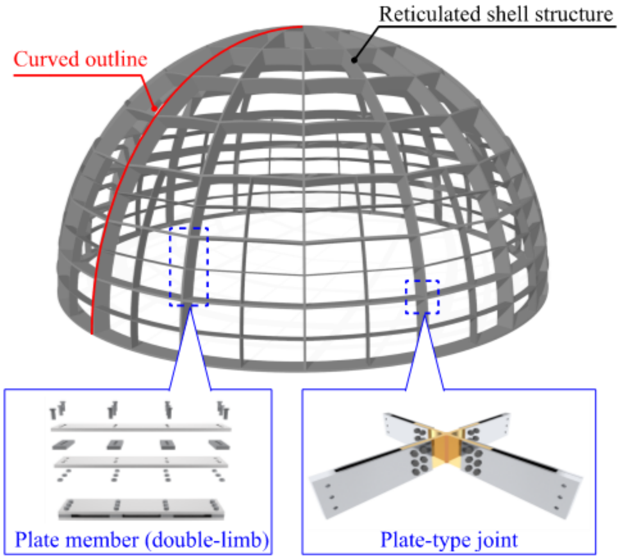

Figure 1: A reticulated shell structure composed of plate members

This study aims to discuss the mechanical performance of reticulated shell structures composed of built-up plate members. Firstly, experimental investigation into the flexural buckling of double-limb built-up plate members under compression are presented. Secondly, the rotational performance of semi-rigid plate-type joints is elaborated. Thirdly, the overall stability behavior of this structure is analyzed.

2. Compression experiments on the plate members

A total of 42 specimens have been tested by Ge et al. [3]. The test results were comprehensively compared with results obtained via the FE modelling. The experimental results indicated that the major buckling mode of the built-up plate members is flexural buckling. Additionally, the built-up plate members exhibited good post-buckling strengths. The typical load-displacement relationship for the specimen is shown in Fig. 2. The developed FE model, which considers the overall geometric imperfection, residual stress, and contact between the limb-plates and connectors, can accurately predict the flexural buckling behavior of built-up plate members, as shown in Fig. 3.

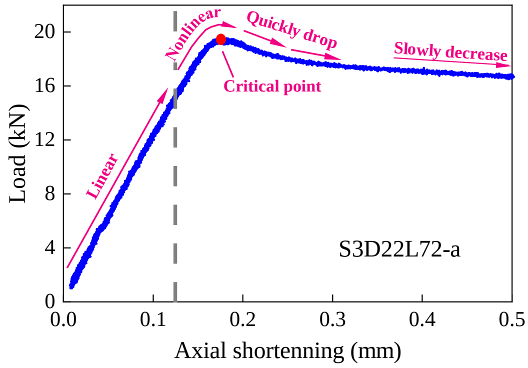

Figure 2: Load–displacement relationship of a typical specimen

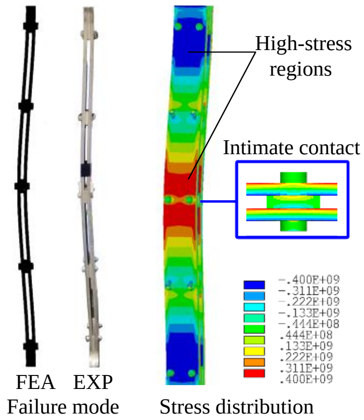

Figure 3: Failure mode and stress distribution of a typical specimen

3. Rotational performance of plate-type joints

Experiments were carried out on a total of 12 joint specimens (Ge et al. [2]), each of them consisting of a two-member central node and two double-limb plate members, as shown in Fig. 4. The moment loads and joint rotations were recorded during the tests. A four-phase analytical model was proposed by combining the results of finite element analysis (FEA) and experiment (EXP), as shown in Fig. 5. the curve slope trend, inflection point, and maximum value obtained from FEA and EXP were basically consistent. The process of nonlinear numerical simulation can also be divided into four phases: initial phase, slipping phase, hardening phase, and failure phase.

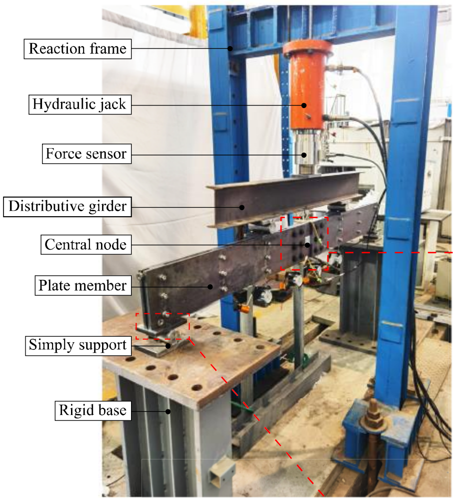

Figure 4: Experimental setup for the plate-type joints

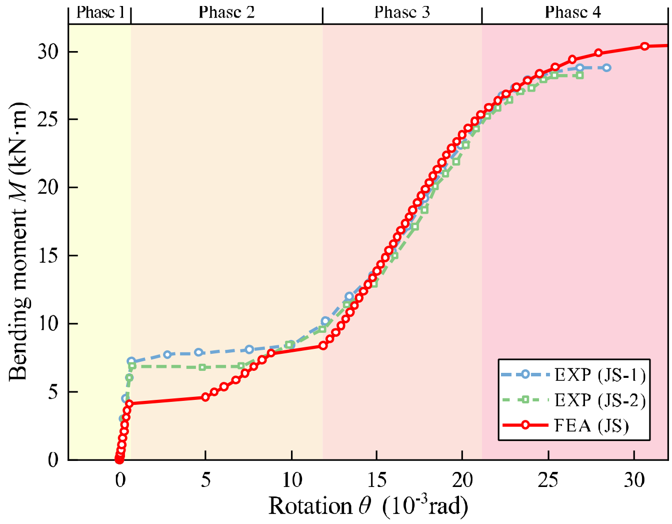

Figure 5: Moment-rotation curves of group JS

4. Stability behavior of reticulated shell composed of plate members

An experiment was conducted on a 3.27 m × 3.27 m spherical SLRS composed of built-up plate members with sub-units (Ge et al. [1]). Distributed load was gradually applied on non-edged joints until the structure loses stability. Corresponding FE analysis is performed for simulating the stability behavior of the experimental structure. Equivalent multi-beam models for double-limb built-up members and nonlinear rotational spring for semi-rigid joints were employed in the numerical simulation. The failure mode and ultimate load of numerical results were compared with the experiment, as shown in Fig. 6. And Fig. 7 shows the deformation patterns of the structure in tests and FE analysis.

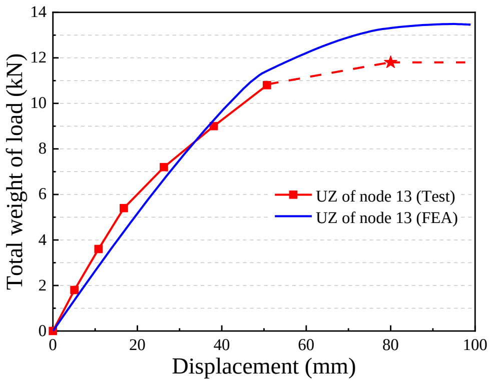

Figure 6: Load-displacement curves of the central node (13)

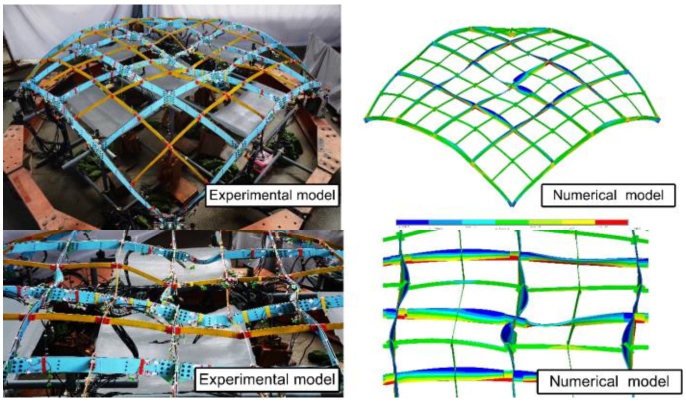

Figure 7: Comparison of the failure modes

Parametric studies were conducted to comprehensively understand the global stability behavior of the reticulated shell structure composed of built-up plate members (Ge et al. [4]), as shown in Table 1. Geometric nonlinear analysis was conducted to understand the global stability of two typical spherical reticulated shell structures from an overall perspective. A total of 2304 different cases were calculated for this section. Within the range of parameters of interest, the failure modes showed regularities to some extent. The typical failure modes of structures are depicted in Fig. 8.

Table 1: Scheme of parametric study

Parameter	Range	Default value
Span (m)	20~50	30
Rise-span ratio	1/3~1/8	1/4
Average grid edge length (m)	1~4	2
Width of limb-plates (mm)	150~300	200
Thickness of limb-plates (mm)	10~20	16
Steel grade	Q235, Q345	Q345
Maximum nodal deflection of geometric imperfection (mm)	0~250	1/300 of the span
Relative joint rotational stiffness	0.01~∞	∞

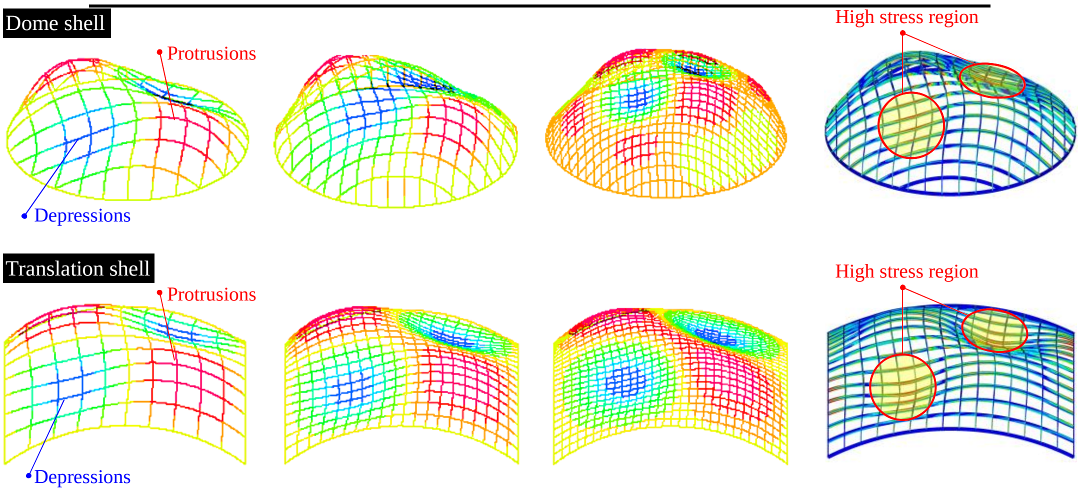

Figure 8: Failure modes and stress contours

4. Conclusion

The stability behavior of reticulated shell structures composed of built-up plate members, which are suitable for building small or medium-span curved-surface structures, has been comprehensively investigated in the former studies. The advantages of this type of structure, e.g., flexibility, efficiency, and precision in outline shape fabrication, make it suitable for constructing curved-surface structures. Future studies may focus on the design and construction process with parametric design method and computerized construction machines.

Acknowledgements

This work was supported by Zhejiang Provincial Natural Science Foundation (Grant No. LQ23E080016) and National Natural Science Foundation of China (Grant No. 52308215).

References

[1] H-B. Ge, H-P. Wan, Y. Zheng, Y. Luo, "Experimental and numerical study on stability behavior of reticulated shell composed of plate members", *Journal of Constructional Steel Research*, vol. 171: 106102, 2020.

[2] H-B. Ge, H-P. Wan, Y. Shen, Y. Luo, "Rotational performance of semi-rigid plate-type joints for reticulated shell structures composed of plate members", *Engineering Structures*. Vol. 283: 115815, 2023.

[3] H-B. Ge, H-P. Wan, Y. Luo, "Experimental investigation into flexural buckling of double-limb built-up plate members under compression", *Journal of Constructional Steel Research*. Vol. 179: 106516, 2021.

[4] H-B. Ge, H-P. Wan, Y. Luo, "Numerical investigation on stability of reticulated shell structures composed of built-up plate members". *Thin-Walled Structures*, Vol. 192: 111121, 2023.