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A structural morphogenesis method based on a linkage mechanism system

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Rationale

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The figure shows the process of generating a rational structural shape through searching for the mechanism shape corresponding to the minimum potential energy. The optimized structure bears the load with only an axial force.

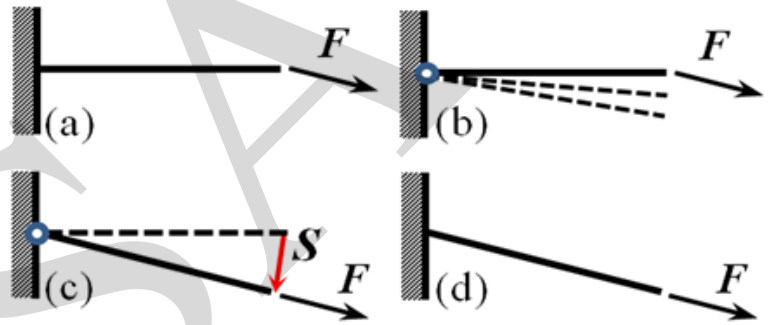


Fig. 1 Process of generating a rational structure

Fig. 1a shows a structure under load $\boldsymbol{F}$ and the bending moment in the structure is not zero. The rigid joint is first turned into a hinged joint so that the structure becomes a mechanism (Fig. 1b). Then, the mechanism shape changes until the potential energy with respect to load $\boldsymbol{F}$ becomes minimal (Fig. 1c). In these two steps, the potential energy increment is calculated as $-\boldsymbol{F}\cdot\boldsymbol{S}$ (where $\boldsymbol{S}$ is the nodal displacement vector). Finally, the hinged joint is turned into a rigid joint again and there is only axial force in the structure. This process generates a rational structural shape through searching for the mechanism shape corresponding to the minimum potential energy. The optimized structure bears the load with only an axial force (Fig. 1d).

Element grouping and functions

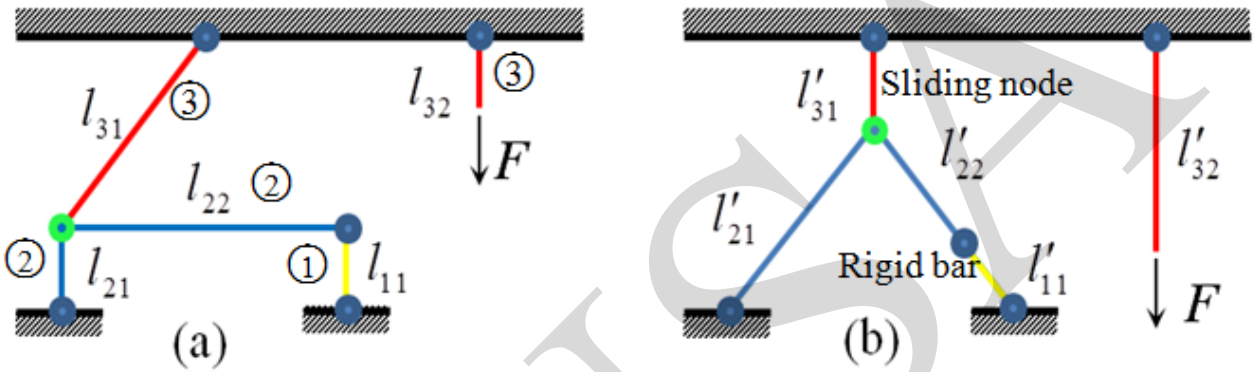
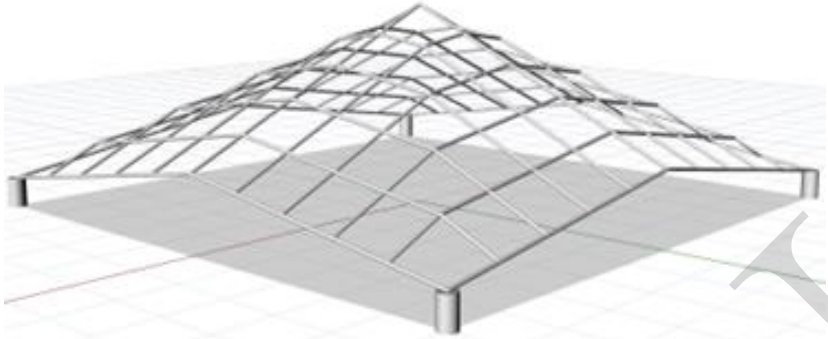


Fig. 2 Grouping of elements in a linkage mechanism system (a) Initial mechanism (b) Resultant mechanism

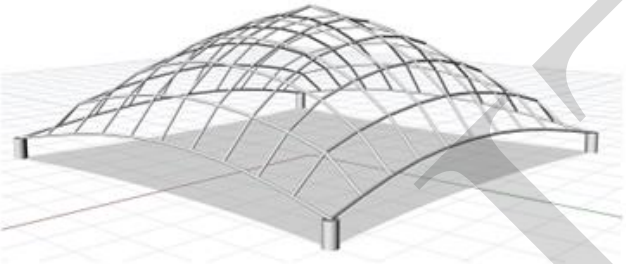
Different element group settings derive different functions. The length of the element in the first element group is constant and it can be seen as a rigid bar. The node linking the two elements in the second element group is a sliding node. The length of the left element transforms to the right element in the third group to make the potential energy of the mechanism decrease. In this process, the two elements can be imagined as a Bowden cable.

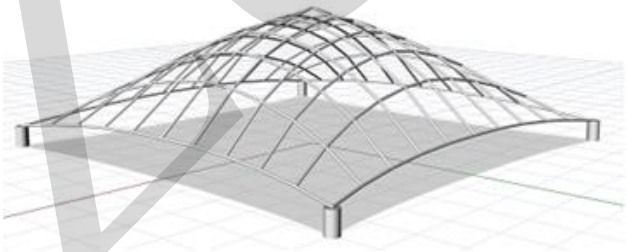
Numerical example

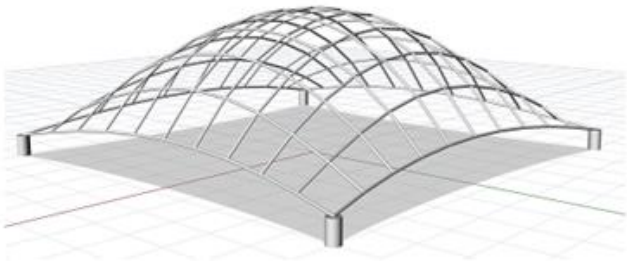


Initial structure

Different element group settings can generate different structural shapes and this is valuable at the schematic design stage.

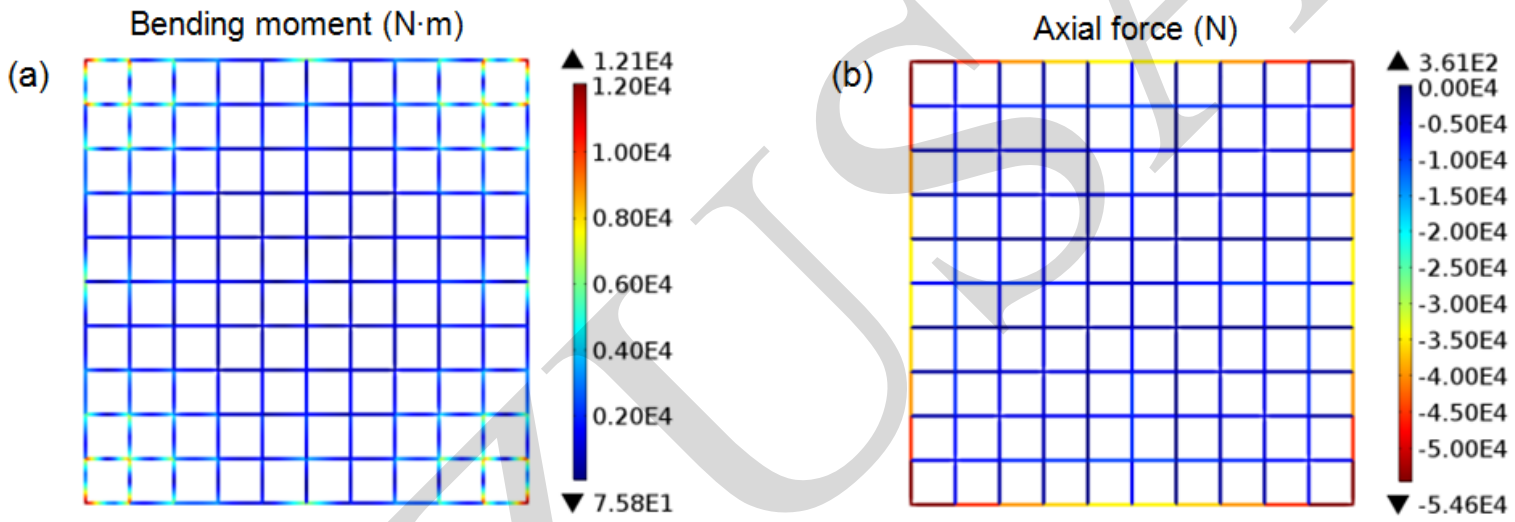






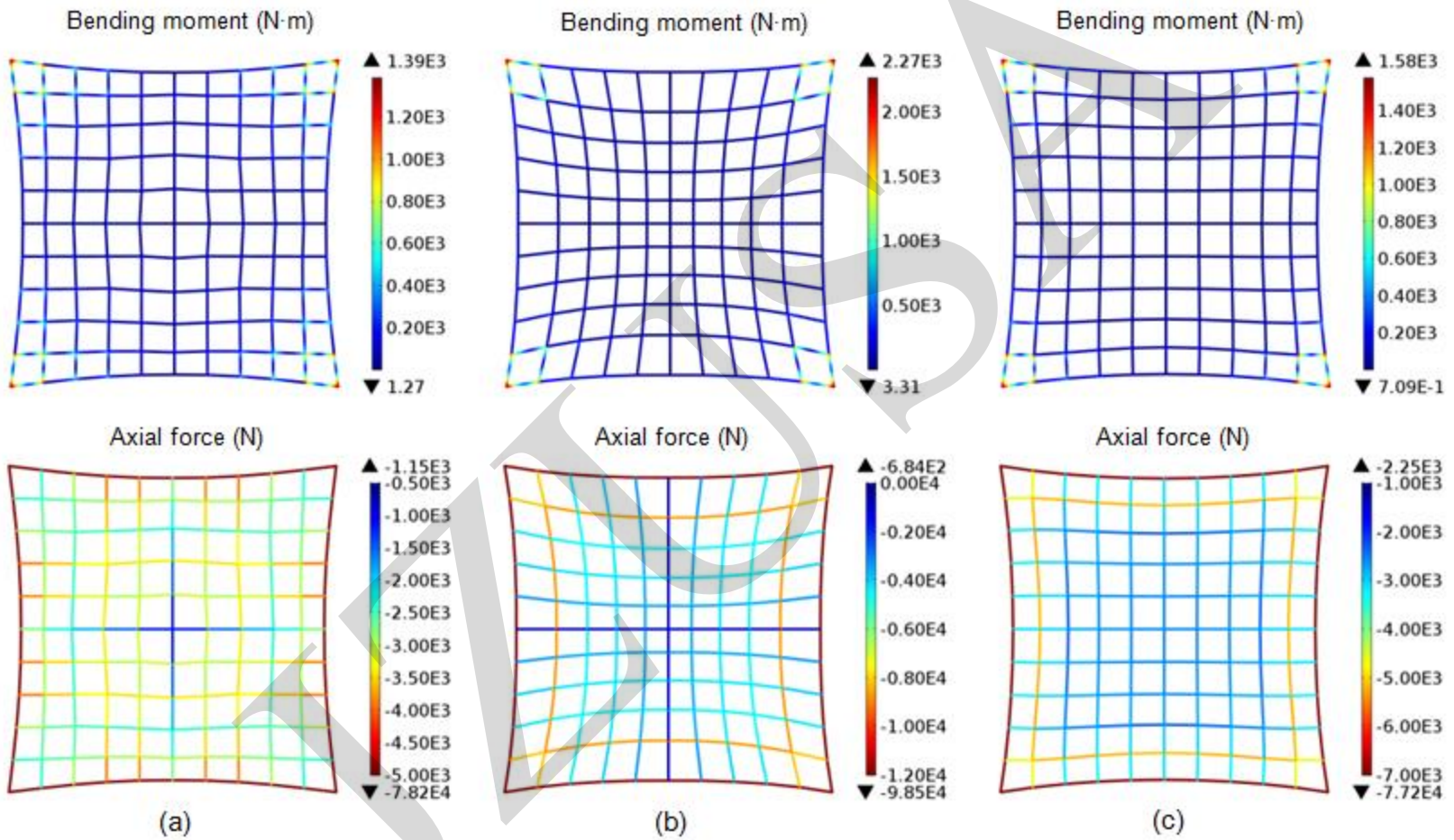
The generated structures

Mechanical properties



Bending moment distribution (a) and force distribution (b) for the initial structure

Mechanical properties



Bending moment and force distributions for optimized structures
(a) Scheme (I); (b) Scheme (II); (c) Scheme (III)

Changes of mechanical properties

In the finite element analysis, the chosen element type is a steel pipe with outer diameter of 8 cm and wall thickness of 1 cm. A vertical downwards nodal force (1.0 kN) acts on each node. The moment and force distributions of the initial structure. The average bending moment is 2.04 kN·m and the maximum bending moment is 12.08 kN·m. The average axial force is 10.98 kN and the maximum axial force is 54.60 kN in the initial structure. The moment and force distributions of the generated structures. For the three schemes, the average bending moments are 0.14 kN·m, 0.15 kN·m, and 0.11 kN·m while the average axial forces are 15.65 kN, 20.40 kN, and 15.70 kN, respectively. The maximum bending moments are 1.39 kN·m, 2.27 kN·m, and 1.58 kN·m, respectively. Through the optimization, the average bending moments decrease by 93.14%, 92.64%, and 94.61%, and the maximum bending moments decrease by 88.49%, 81.21%, and 86.92%. The generated structures carry the given load in compression with smaller bending moment.

Conclusions

This study presented a morphogenesis method, called the elements-grouped method, for designing grid shell structures. The method searches for the shape of the linkage mechanism system corresponding to the minimum potential energy and the structure with the resultant shape features predominantly axial forces under the given load. The length constraint function allows it to satisfy specific geometry requirements of architecture. Different element group settings can lead to various different rational structural shapes for the same initial model, which can offer choices to architects at the schematic design stage. Moreover, the introduction of temporary elements and temporary forces provides an axial force control function and extends the applicability of the method. In total, the functions of the proposed method in length constraint, axial force control, and length self-adjustment enrich the means to generate a large number of structural shapes, and offer more architectural schemes for designers. The design examples given show the efficiency of the proposed method.