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Studies on In-plane Stability Behavior of Arches with Web Openings

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Abstract. As a new type structural member, the steel arch with web openings combines the features of both arches and members with web openings and its applications has been found. Studies on in-plane stability behavior of two-hinged arches with web hexagonal openings are made using Eigen buckling model of the finite element software ANSYS. The buckling load and buckling mode are obtained and the in-plane buckling mode is antisymmetrical. It is shown that buckling load decreases gradually as the circumcircle radius of openings increases and it increases as the gap between openings increases through analysis of buckling load with different parameters such as r/h, g/h, f/l. It can be found that the structural efficiency is the highest when the radius of openings is 0.3h with the aid of optimized function.

The Finite Element Model

To I-sectional arches with web openings, it is prone to local buckling because of the thin plate, and the emergence of openings makes section change constantly along the axis. So the usual beam element can't simulate it accurately. It is more suitable to use shell element. Comprehensive consideration, this paper employs shell181 element and the free mesh division method [1]. Computation model is shown in Fig.1, f/L is rise to span ratio, r is circumcircle radius of hexagonal openings, g is gap between openings, h is height of I-section, b is width, t_w is thickness of web, t is thickness of flange. Make f = 6 m, l = 20 m, section type H × b × t_w × t = 600×200×18×24, elastic modulus E = 2.06 ×10^5 MPa, yield strength f_y = 235 MPa. Changing parameters of arches can obtain different arch models. The structure is analyzed statically, constrained on both ends of arch and limited out-plane displacement of the arches in order to prevent out-plane instability, and then put uniform radial loads to make eigen buckling analysis.

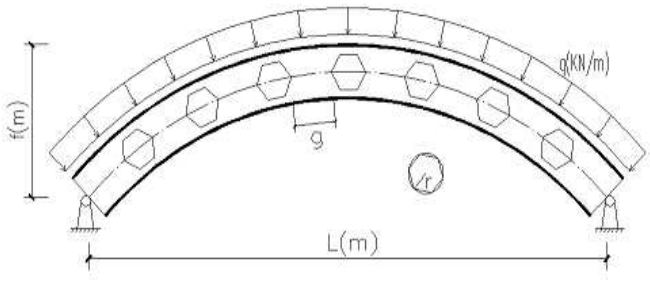

Fig. 1 Computation model

The Effects of Openings on Buckling Load

In-plane buckling modes and critical buckling loads of the arches are influenced by various factors, including the nature of load, load distribution, the shape of arch axis, constraints and so on [2]. In addition to these factors, buckling load of arches with openings is also influenced by the size of openings and the gap between openings.

Through solving, in-plane buckling modes of arches with web openings are antisymmetric, and it is same with buckling modes of arches without web opening. We can also know buckling loads of each arch through the Eigen buckling, shown in Fig. 2.

General trend is seen from the curve: when the circumcircle radius of openings increases, buckling loads decrease gradually; when the gap between openings increases, buckling loads increase gradually, and buckling loads of arches with web openings are less than buckling loads of

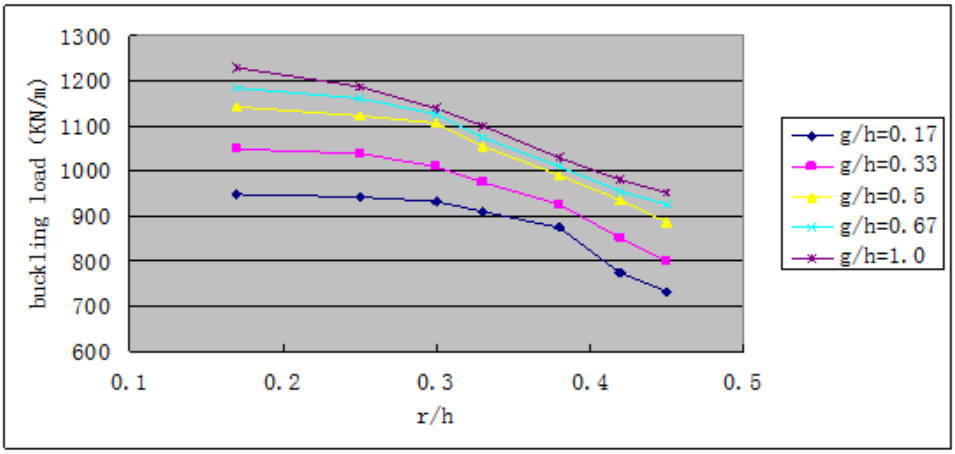

Fig. 2 Buckling loads of arches with different openings

arches without web openings. Everything proves that the emergence of the openings arches causes arches weaken. The bigger openings become, the more seriously arches weaken; the smaller gap between openings becomes, the more seriously arches weaken. Also we can see that the incremental trend of buckling loads becomes slow when the gap between openings g > 0.5h, and it also becomes slow when the opening size r reduced to 0.3h.

Optimization of Openings

The essence of the web openings is to remove part of the small contribution to structure, so the structural efficiency is improved. If openings size is too small, it doesn't play a great part in improving the structural efficiency. It will weaken the arches greatly if openings size is too big, so structural efficiency is reduced. Optimization of openings is to find out that what radius of openings is when the structural efficiency is the highest. Take gap between openings for 0.5h as an example to solve the optimal radius of arches.

Firstly considering the dimensionless elastic buckling load $\overline{N_{cr}}$ [3](formulated 1), which removing influences of sectional attributes and material yield strength.

$$\overline{N_{cr}} = \frac{N_{cr}}{Af_y} = \frac{q_{cr}R}{Af_y} \tag{1}$$

According to solved buckling loads, relation curves of $\overline{N_{cr}}$ and r/h are made, as shown in Figure3: It can be seen that when r/h increases, the dimensionless elastic buckling loads of structure decrease gradually. Decline rate of r/h>0.3 is faster than decline rate of r/h<0.3. However, the whole curve is monotone decreasing. So we can't find out the highest structural efficiency.

To solve the highest structural efficiency, we should find the right balance between the steel usage and the bearing capacity, which steel usage is the least with the same capacity. So it also needs to know how much contribution unit weight materials to the buckling load. Making up the functional relationship of correctional dimensionless elastic buckling load $\overline{\overline{N_{cr}}}$ and dimensionless mass ratio ρ [4], formulated 2.

$$\overline{\overline{N_{cr}}} = \frac{\overline{N_{cr}}}{\rho} \tag{2}$$

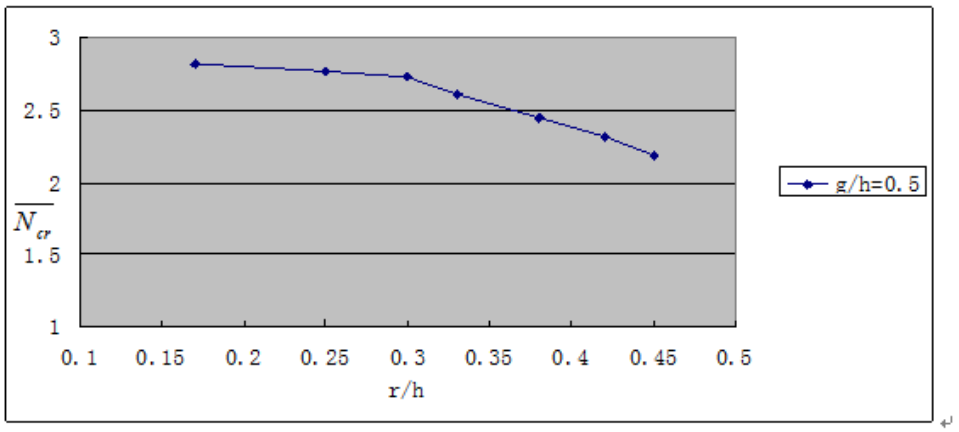

Fig. 3 Relation curves of $\overline{N_{cr}}$ and r/h

Parameter ρ is ratio of the dimensionless quality of part of without openings and dimensionless quality of overall arches. Its value is between 0 and 1. The smaller ρ becomes, the less the steel usage becomes. We can see from the above function when $\overline{N_{cr}}$ is unchanged, the smaller ρ is, the bigger $\overline{\overline{N_{cr}}}$ is, which achieving the same $\overline{N_{cr}}$, the less the steel usage is, the higher the structural efficiency becomes. Fig.4 is relation curves of $\overline{\overline{N_{cr}}}$ and r/h:

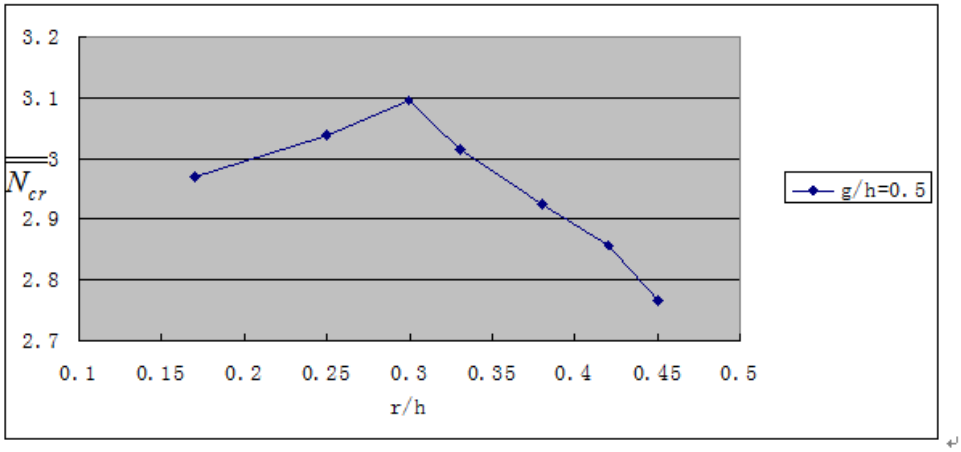

Fig. 4 Relation curves of r/h and $\overline{\overline{N_{cr}}}$

It can be seen from the Fig 4, $\overline{\overline{N_{cr}}}$ also gradually increase when radius increase, which structural efficiency is improved gradually. This is because opening on the web of arches is to remove part of the small contribution to structure and improve the structural efficiency. On the contrary, when r/h>0.3, $\overline{\overline{N_{cr}}}$ rapidly decline as r/h increase. This explains it will weaken section seriously when openings are too big, it will greatly reduce the structural efficiency instead. So the radius of openings can not be too big or too small. It can be seen from the law that the structural efficiency is the highest when radius of openings is 0.3h.

The above study is worked under the condition of span 20 m, rise 6 m. Change rise-span ratios of the arch (span L 20 m, rise f change to 2 m, 4 m, 8 m and 10 m), unchanged other conditions, changing rise-span ratios whether influence on optimized radius are investigated. Still through the above eigen buckling analysis, $\overline{\overline{N_{cr}}}$ and r/h relation curves (Fig. 5) are obtained. By the same method, change t, t_w and unchanged other conditions, the influences of plate thickness on optimized radius are investigated. Relation curves of $\overline{\overline{N_{cr}}}$ and r/h is in Fig 6. Every curve in Fig 5 and Fig 6 are first up and then down. But there is a common highest when r/h reach 0.3. To sum up, the optimal radius of openings is 0.3h.

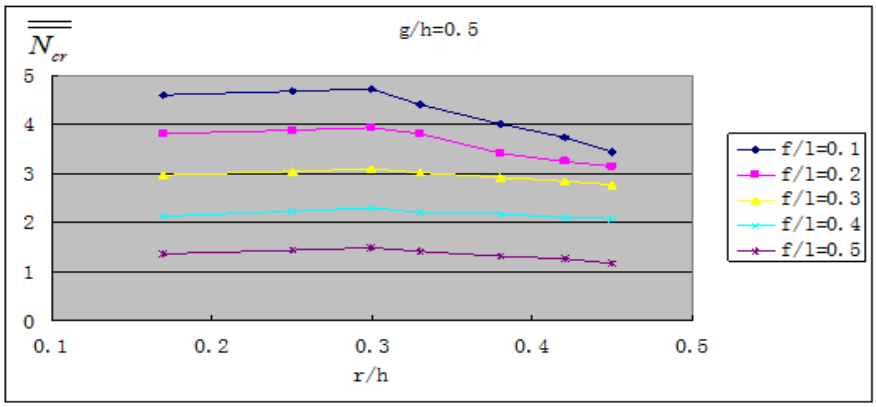

Fig. 5 Relation curves of $\overline{\overline{N_{cr}}}$ and r/h under different f/l

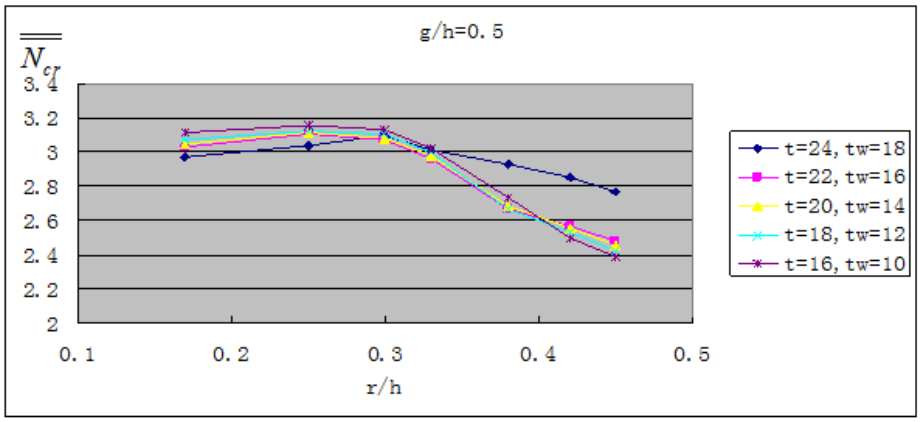

Fig. 6 Relation curves of $\overline{\overline{N_{cr}}}$ and r/h under different t, t_w

Conclusion

The most easily in-plane instability modes of two-hinge arch with web hexagonal openings are antisymmetric instability. The emergence of openings reduces doesn't change the mode of arch, but the buckling load decreases gradually as the circumcircle radius of openings increases and it increases as the gap between openings increases Through Analysis of eigen buckling of arches with web openings of different parameters and optimized function, we find that the structural efficiency is the highest when r/h is 0.3.

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