Studies On Out-of-Plane Stability of Arches with Web Openings Accounting for Plate Local Buckling

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Abstract. The out-of-plane elastic buckling behavior of I-section circular arches with web openings under radial uniform load, accounting for plate local buckling, is simulated and analyzed by finite element software ABAQUS. The buckling loads at different rise-to-span ratio, the height-to-thickness ratio of the web, hole radius and spacing are calculated. The results show that the out-of-plane buckling load decreases with the increase of hole radius and increases with the increase of hole spacing. By establishing the hole optimization function and adopting the modified dimensionless elastic buckling load, it is found that the structure has the highest efficiency when the hole radius is between 25% and 35% of the web height, and the hole spacing is between 30% and 50% of the web height.

1. Introduction

Steel arches are a kind of architectural structure with a long history. The arch structure produces horizontal thrust under the action of vertical load. The bending moment generated under the load is converted into axial force by its unique curve form, which makes the arch have high bearing capacity and strong crossing capacity. In recent years, the web opening arches are gradually favored by designers because of its beautiful architectural shape. The introduction of a hole in the web opening arches can realize the use function and the structural function: in the use function aspect, it can make the component shape more beautiful, at the same time, it is convenient for the pipeline to pass through without reducing the clear height of the structure; in the structural function aspect, it can make the plate play a greater role and increase the efficiency of the component [1].

At present, most of the research on arches by domestic and foreign scholars only considers the overall buckling, and do not consider the local buckling. The web of I-section is mainly subjected to shear, and the flange is mainly subjected to bending moment. The increase of web height can improve the bending resistance of the section. Considering the economy, it is not appropriate to increase the thickness of the web while increasing the height of the web, that is to say, high and thin webs should be used, which is currently a more advanced design method[2]. However, this will cause the local buckling of the web. This article mainly optimizes the hole size based on the consideration of local buckling.

2. Establishment and verification of finite element model

The shell element S4R in ABAQUS is used to establish the calculation model of I-section solid web arches and web opening arches. The material is linear elastic, elastic modulus $E=2.06 \times 10^6 \text{MPa}$, Poisson's ratio $\nu=0.3$, yield strength $f_y=235 \text{MPa}$. The unit side length of the flange and web is selected as 1mm, and the unit shape is quadrilateral. Because the out-of-plane elastic buckling load of hinged arch is very small, it is rarely used in engineering, so the out-of-plane arch toe of the steel arch is
restrained as a fixed connection. The finite element model is shown in Figure 1.

Figure 1. Finite element model of solid web arches.

Figure 2. Finite element model of web opening arches.

In order to ensure the accuracy of the finite element simulation, a comparative analysis was carried out with the elastic bending torsion test in the literature [3]. In reference [3], the I-section of the arch specimen was selected, and a vertical load was applied at the midpoint of the arch. The geometric dimensions and elastic modulus of the test piece are shown in Table 1.

![Table 1. Geometric dimensions and elastic modulus of specimens.](image)

| $b_f$ (mm) | $H$ (mm) | $t_f$ (mm) | $t_w$ (mm) | $R$ (mm) | $E$ (MPa) |
|-----|-------|-------|-------|-------|--------|
| 7.11 | 15.88 | 1.42  | 1.39  | 1000  | 62940  |

ABAQUS is used to calculate the out-of-plane elastic buckling load of solid web I-section arch with the above geometric dimensions at the center angle of 30° to 70° and the comparison results are shown in Table 2.

![Table 2. Comparison of elastic buckling load results between test and finite element analysis (N).](image)

| Center angle | 30°  | 40°  | 50°  | 60°  | 70°  |
|-------------|------|------|------|------|------|
| test        | 80.16| 39.69| 25.77| 15.58| 7.64 |
| FEA         | 79.13| 38.96| 23.40| 14.60| 8.41 |
| Difference  | -1.03| -0.73| -2.36| -0.97| 0.77 |
| error       | -1.29%| -1.84%| -9.22%| -6.26%| 10.03%|

The absolute value of the maximum difference between the test and finite element results is only 2.375N, and the absolute value of the relative error is within 10.03%. The buckling load simulated by the finite element method is in good agreement with the test results. The error may be caused by the errors in the fabrication and installation of the test components, as well as the existence of geometric initial defects and residual stresses.

3. The effect of holes on out-of-plane elastic buckling load
For arches without out-of-plane support or insufficient support rigidity, when the load acting in the arch plane reaches a certain value, under the action of the torque around the arch axis and the lateral bending moment, the arch will produce spatial bending and torsion deformation outside the plane, that is, out-of-plane elastic buckling occurs. In general, after out-of-plane buckling occurs, with the rapid development of the bending and torsion deformation of the arch, it will quickly loses its bearing capacity and collapse. Therefore, the elastic buckling load is regarded as the ultimate load of the arch's bearing capacity [4].
By changing the hole radius \((r)\) and spacing \((g)\), the weakening effect of the web opening on the out-of-plane elastic buckling load of the arch is analyzed. The arch parameters are selected as follows: rise-to-span ratio \(f/l=0.3\), Slenderness ratio \(\lambda=40\), I-shaped section size \(600\times200\times4\times12\) (mm), hole radius \(r=0.15h, 0.2h, 0.25h, 0.3h, 0.35h, 0.4h\), the hole spacing \(g=0.15h, 0.3h, 0.5h, 0.7h, h\). First, fix \(r=0.3h\), and take \(g\) as \(0.15h, 0.3h, 0.5h, 0.7h, h\), and plot the elastic buckling load calculated by the finite element in Figure 4.

Analysis of Figure 3 shows that the buckling load will increase with the increase of the hole spacing. When \(g\) is small, the buckling load increases rapidly; when \(g\) exceeds \(0.5h\), the buckling load increases more slowly; when \(g\) is equal to the height of the web, the out-of-plane buckling load reaches the highest.

Fix \(g=0.3h\), and take \(r\) as \(0.15h, 0.2h, 0.25h, 0.3h, 0.35h, 0.4h\), and plot the finite element calculation results in Figure 4. It can be seen from the figure that the buckling load decreases as the radius of the hole increases. Especially when \(r\) exceeds \(0.3h\), the buckling load decreases extremely significantly.

4. Optimization of hole size considering local buckling of web

The existence of holes can make the section to obtain greater bending rigidity, but weaken its shear resistance. Therefore, the size of holes needs to be optimized to seek to use the least amount of steel to obtain the largest buckling load. This paper chooses a dimensionless method to establish an optimization function for hole optimization [1]:

\[
\frac{\tilde{N}_{cr}}{N_{cr}} = \frac{1}{Af_{y} \rho}
\]

\[
\rho = 1 - \frac{\pi^{2} t_{w}}{(ht_{w} + 2bt_{w})(g + 2r)}
\]

The above formula, \(\tilde{N}_{cr}\) is the modified dimensionless elastic buckling load, which reflects the contribution of the material per unit weight to the elastic buckling load; \(\rho\) reflects the proportion of the hole in the weight of the entire member. When \(\rho\) the smaller, \(\tilde{N}_{cr}\) the larger, the greater the contribution of the material per unit weight to the elastic buckling load, the higher the efficiency of the structure.
Considering the steel arches with different rise-to-span ratio and different height-thickness ratio of the web, they are divided into A series and B series to study the optimal size of steel arch holes considering the local buckling of the web. Choose $f/l=0.3, 0.4$ for A series, choose $h_0/t_w=150, 200$ for B series.

![Figure 5. $f/l=0.3$ (A series).](image)

![Figure 6. $f/l=0.4$ (A series).](image)

It can be seen from the A series figures that each set of curves has its corresponding extreme point, corresponding to the optimal hole size. When $f/l=0.3$, when $g=0.15h, 0.3h, 0.5h, 0.7h$, the extreme points appear at $r=0.3h, 0.3h, 0.35h, 0.35h$; when $f/l=0.4$, When $g=0.15h, 0.3h, 0.5h, 0.7h$, the extreme points appear at $r=0.25h, 0.3h, 0.35h, 0.35h$. In general, the extreme points all appear between $r=0.3h-0.35h$. It can also be seen from the figure that when $g=0.3h, 0.5h$, $\tilde{N}_{cr}$ is larger, and the structure efficiency is higher. As the rise-to-span ratio increases, the structural efficiency is slightly lower, but the amplitude is not large.

![Figure 7. $h_0/t_w=150$ (B series).](image)

![Figure 8. $h_0/t_w=200$ (B series).](image)

It can be seen from the B series figures that each set of curves also has extreme point. The curve change law is basically the same as the A series, and the extreme points appear between $0.25h$ and $0.35h$. It can also be seen from the figure that when $g=0.3h, 0.5h$, $\tilde{N}_{cr}$ is larger, and the structure efficiency is higher. As the height-to-thickness ratio of the web increases, the structural efficiency decreases, which is consistent with the law that the height-to-thickness ratio of the web reduces the elastic buckling load of the arch.

To sum up, according to the calculation results of the hole optimization function, the recommended values for the hole size are: $r$ is between $0.25h$ and $0.35h$, and $g$ is between $0.3h$ and $0.5h$. 
5. Conclusion
In this paper, ABAQUS finite element software is used to study the out-of-plane elastic buckling performance of a circular arc arch with web openings under uniform radial load. The shell element is used to consider the influence of local buckling on the elastic buckling load. In this paper, the modified dimensionless elastic buckling load is used to establish the hole optimization function, and the parameters such as rise-to-span ratio, height-to-thickness ratio of the web and hole size are changed to study the optimal hole size. Studies have shown that when the hole radius is between 25% and 35% of the web height and the hole spacing is between 30% and 50% of the web height, the structural efficiency is the highest.

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