Research on practical analysis method of metal frame radome structure considering skin effect

Radar systems play an important role in national defense security and civilian fields. Radome is built to protect the radar antenna. The radomes studied in this thesis (Fig 1.a) consist of metal skeleton and architectural membrane skin. During the assembly of the radome, the structure is composed of several triangular elements and the elements are connected by flanges (Fig 1.b). Traditional structure analysis only considers the bearing capacity of skeleton while the effect of skin effect is omitted, which caused the calculated component cross-section is unnecessarily large. Therefore, it is necessary to reveal the mechanism of skin effect through analysis and experiments and establish a more practical design method of radomes considering the skin effect.

Fig 1.a 17m span Radome

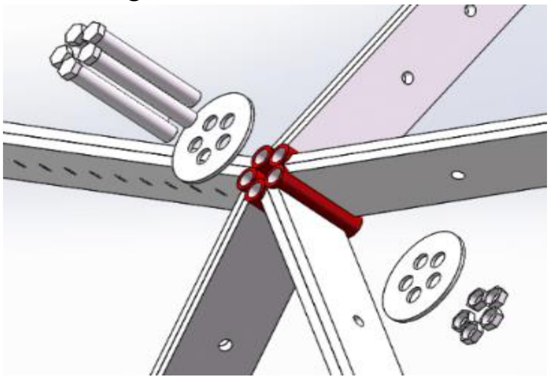


Fig 1.b Connection of Radome

Fig 1. Radome studied in this thesis

1. Static load test and Finite element analysis (FEA)

We applied 2 loading tests for the radome structure, one for the whole radome structure and another one for a double-triangle unit which is a typical bearing unit. In the test about whole structure, a self-designed loading system was applied, the displacement and strain of radome was measured. To investigate the effect of skin, the original structure and the skin removed structure were loaded separately. The result shows that the stability bearing capacity of the structure increases more than 5 times obviously.

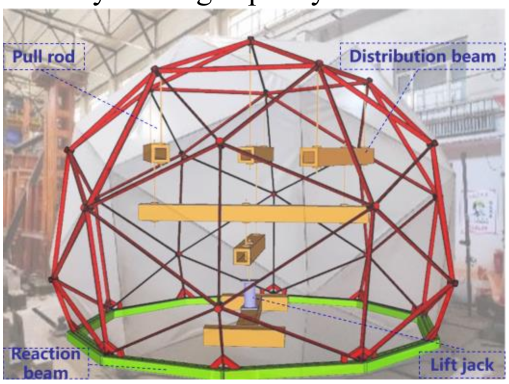


Fig 2.a Design of specimen

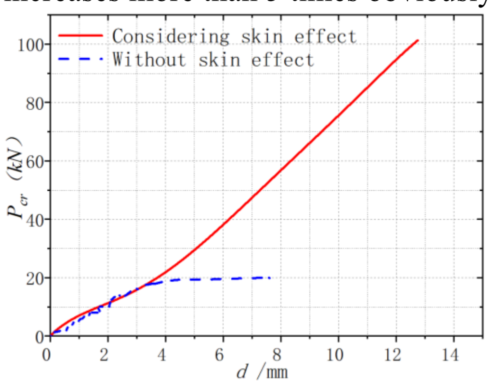


Fig 2.b Comparison of results

Fig 2. Static loading test for whole structure

The test of double-triangle unit is to explore the stress and strain field under ultimate bearing load, and verified the accuracy of the finite element model. The result shows that, the skin effect greatly improves the stable bearing capacity of the test specimen: the stable bearing capacity of the skin element is 7.8 times that of the skeleton element.

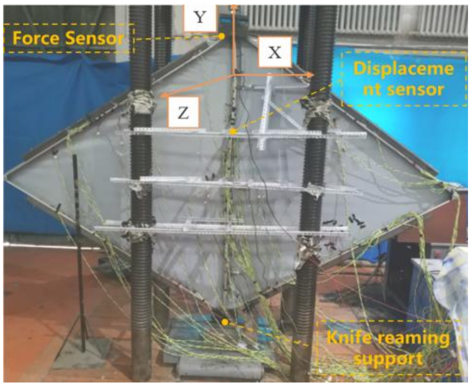


Fig 3.a Design of specimen

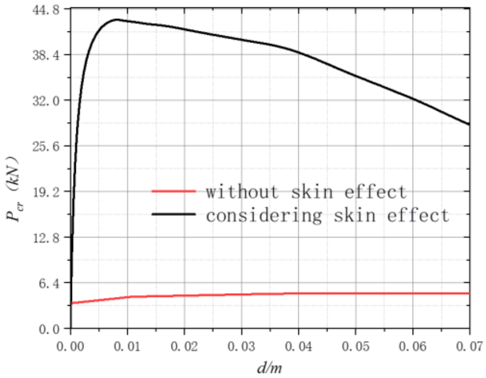


Fig 3.b Comparison of results

Fig 3. Static loading test for double-triangle unit

Considering that the whole radome and element of the radome show buckling failure in the test, we carried FEA which mainly about whole process stability analysis of the radome structure, with the material nonlinearity and geometric nonlinearity taken into account. The comparison between the FEA and the test results show that the numerical simulation method considering the skin effect of the radome structure has good accuracy. For the whole structure, the error between the simulation results and the test results is only 3.6%; for the double-triangle unit, the error is 3.4%.

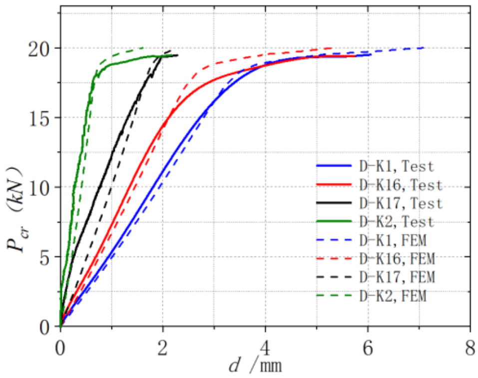


Fig 4.a Comparison of simulation results and test results(whole structure)

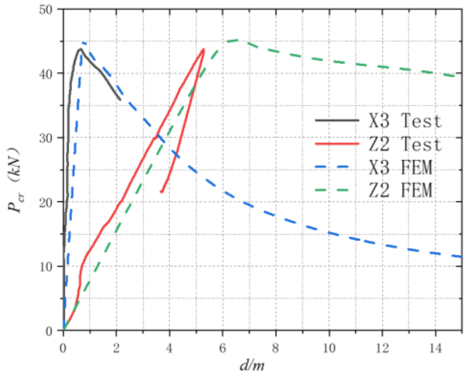
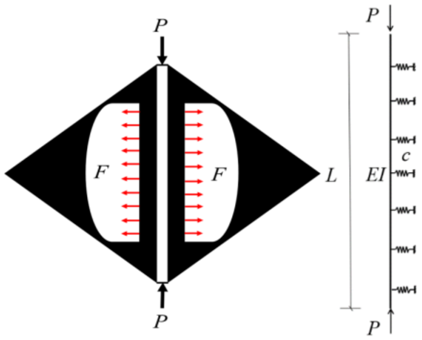


Fig 4.b Comparison of simulation results and test results(double-triangle unit)

Fig 4. Load-displacement curves for different measuring point

2. Analysis of skin effect and formulation

The improvement of the ultimate stability bearing capacity is because of the support of skin on skeletons. In the study, the supporting effect of skin on the rod is simplified as continuous supporting spring, so the double-triangular element can be equivalent to a buckling rod on continuous spring support (Fig 5), the buckling load of this kind of rod can be calculated with the equilibrium equation established for the isolated body of the structure. The analytical solution for the rod is formula (1), it shows that the buckling load of the rod depends only on the stiffness of the rod and the skin. In order to explore the correctness and applicability of this equivalent support, more FEA are carried for double-triangular element.



$$P_{cr} = 2\sqrt{cEI} \quad (1)$$

P_{cr} : critical buckling load for the rod

c : spring constant, only related to the skin surface stiffness

E : means the modulus of elasticity

I : inertia moment of the rod section.

Fig 5. Double-triangular element simplified to a continuous spring support rod

The ultimate bearing capacity curves (Fig 6) of 15 different slenderness ratio specimens show that there are 3 failure mode for the rod, the first (Fig 5.a) is strength failure, the stability capacity can be neglected; the second (Fig 5.b) is high-order buckling, the deformation of the rod is mainly in-plane; the third (Fig 5.c) is low-order buckling, the deformation of the rod is mainly out-plane.

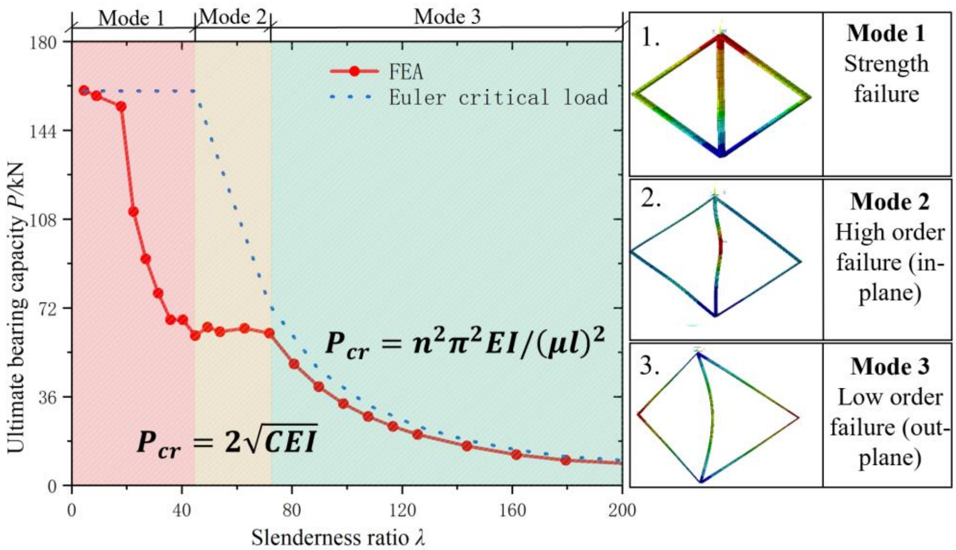


Fig 6. The ultimate bearing capacity curve and failure modes

In conclusion, the improvement of stability bearing capacity of radome by skin effect can be interpreted as skin provides in-plane continuous support in weak axis for rod, which changes the failure mode of the rod to a high-order buckling in plane. When the in-plane support is strong enough, the displacement of the rod turns to out-plane and the failure mode changes to low-order. From a series of parameter analyses, a semi-empirical formula for calculating the stability capacity of radome rods was presented.

$$P_{cr} = min\begin{Bmatrix} 2\sqrt{cEI_z} + kEi_z^2 \\ \frac{\pi^2 EI_x}{(\mu l)^2} * 0.85 + a * \tan(90^\circ - \frac{\theta}{2}) * \frac{cl^2}{\pi^2} \end{Bmatrix} \quad (2)$$

In this formula, the $c = 2E_m t$, means the same as (1); E_m is the elastic modulus of skin; t is the thickness of skin; E is the elastic modulus of the rod; $i_z = \sqrt{\frac{I_z}{A}}$ is the radius of gyration of the rod section to the weak axis (Z-axis); kEi^2 represents the supporting effect of the rods on the two sides of the double triangle on the central rod; θ is the Angle between the triangle elements. k is the supporting coefficient; μ is the constraint coefficient; a is the Angle coefficient; all those coefficients were got from curve fitting.

3. Practical methods and self-developed software

In order to solve the poor convergence of radome in FEA, we developed an equivalent FE model (Fig 7) of stiffness and deformation for the radome. In this model, the supporting effect of skin on the rod is equivalent to the extra flange on the rod, so that the FE model can only calculate the skeleton. The calculation time of this equivalent model is only 10% percent of the original one, and the error of bearing capacity and displacement are less than 10%. In addition, we also carried out secondary development for the radome using the equivalent model, developed a software for radome designers using Microsoft Visual Studio 2019, the software has been applied to actual projects.

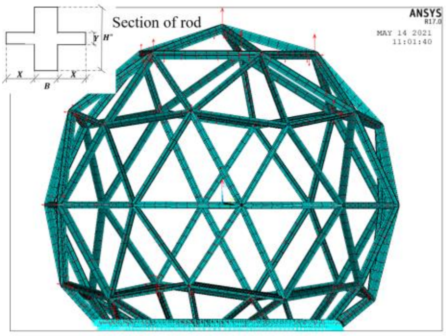


Fig 7. Equivalent Radome model

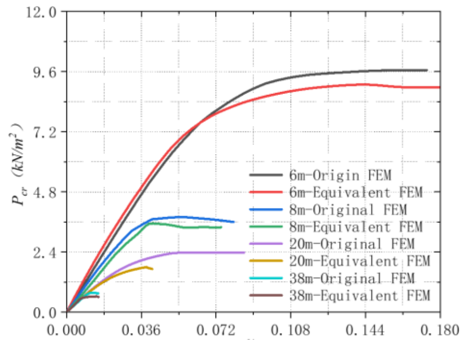


Fig 8. Load-displacement curve for Original and Equivalent FEM

4. Conclusion

The skin effect of radome is analyzed using experiments and analysis, the mechanism is investigated and a practical analysis method is developed. The main conclusions of this study are:

1. The skin effect can increase the bearing capacity of radome rod obviously, either for the whole structure or the double-triangle unit.
2. The mechanism of the skin effect is that the support of the skin changes the failure mode of the rod to high order failure, if the in-plane support is strong enough, the failure mode will turn to low-order failure out of plane.
3. The practical analysis method has a good accuracy and can save 90% of the calculation time.s