Buckling technique and experiment on the concrete pump truck boom

Hong-Feng Ma¹,², Yong-Neng Lu¹,² and Xiao-Qiang Guo¹

¹Jiangsu Xuzhou Construction Machinery Research Institute, Xuzhou, 221004, China
²State Key Laboratory of Intelligent Manufacturing of Advanced Construction Machinery, Xuzhou Construction Machinery Group, Xuzhou, 221004, China
mhfxxyq@163.com

Abstract. Buckling analysis is very important to the structure of long boom, especially for heavy bearing load. In this paper, buckling and fracture process of concrete pump truck boom is studied based on plate-beam buckling theory. The experiment bench of concrete pump truck boom is designed, and the fracture experiment of concrete pump truck boom is carried out. According to the trace of structural strain, instability and fracture critical load of concrete pump truck boom is acquired. The mechanical characteristics of structural material are obtained by experiment, which are used in the nonlinear finite element analysis of concrete pump truck boom. The results show that, buckling instability of partial plate which lies at the side of compression happens easily when concrete pump truck boom is loaded. However the boom structure still has bearing ability in post buckling. Meanwhile, the geometric deforming calculation is proved through research and experiment results in this paper. This method of buckling analysis is often useful to the similar structures.

1. Introduction

The buckling stability problems of plate and shell structures, which are popular in the field of construction machinery, should be considered thoroughly during the process of product design. Buckling of box welding structure means plate and shell structures and their components become whole or partial instability under various kinds of loads, and lose load bearing ability in the end. Both experimental analysis and Finite Element Method were applied to study buckling problems in the paper.

Concrete pump truck is the special construction machine which is used to transfer and deliver the concrete. The boom is the key part of concrete pump truck, and its safety is one of crucial factors to concrete pump truck’s competitiveness in the market. There are many problems to restrict lightweight design, such as buckling, which affects structures’ safety and stability. Long-arm concrete pump truck is the trend, but there is little experimental study about large structures’ buckling problems in the world. Presently, some structures’ stability experiments have been carried out, such as truss compression, plate deformation, I-beam bending, stability of box structure and so on, unfortunately lack of large construction machine’s buckling experiments. In this paper, the behaviors of critical buckling and post buckling are studied, based on buckling experiments of concrete pump truck boom.
2. Buckling theory
Buckling is a common phenomenon which occurs when structures lose its stability. Once the large construction structures lose bearing ability, it will be a catastrophic accident. Buckling is classified by bifurcate buckling (Figure 1a), primary buckling (Figure 1b) and snap through buckling (Figure 1c), as is shown in Figure 1.

Fig 1. Buckling classification

2.1 Buckling
When the plate occurs buckling, the surfaces of plate’s both sides distort and bend, like the phenomena of concave and convex, as shown in Fig 2, the rectangle plate arises buckling deformation under uniform compression. Torque or bending moment of any point on the plate relates to the point’s coordinate and it is two-dimensional partial differential equation.

Fig 2. Buckling of simple supported rectangle plate

Instability of ideal thin plate belongs to stable bifurcate buckling. It can be solved by partial differential equation, which ideal plates are pressed under uniform compression and bifurcation buckling load. Energy method has to be used to solve plates’ buckling problems of other stress conditions and boundary conditions. To those plate and beam structures with other kinds of plates support, the stress and boundary conditions change enormously. And after buckling, the strength of plates still can be reinforced. Partial stiffened plates have been widely used to enhance box structure, which is effective method in engineering application. Buckling analysis of complex structure has to use computer numerical calculation. Figure 3 shows partial instability deformation of beam which is welded by plates.

Fig 3. Partial instability deformation of beam

2.2 Calculation method of buckling
We can get loads of plates’ bifurcate buckling based on small deflection theory. But we can acquire post buckling strength and deflection by large deflection theory. Traditional buckling analysis uses linear buckling eigenvalue method, and it uses stability equilibrium criterion which is based on linear small deflection theory. This criterion makes a hypothesis that it is linear and there is no defect in
geometry. Although we can get the qualitative analysis of buckling modal and buckling position by above results, but the buckling loads have some tolerance compared to real values and we cannot gain the accurate structure stress or the trace of structure deformation.

In modern times, stability theory analyses the difference of buckling load dispersion. More complicated analysis methods are used to study nonlinear buckling stability, such as nonlinear large deflection stability method, materials’ physical nonlinear or geometry nonlinear method.

3. Concrete pump truck buckling experiments

3.1 Specimen
Concrete delivery pipes are fixed on boom along the axial direction stretch out and turn around by boom system to deliver the concrete to working field continuously, and the appearances of boom structure can change continuously. Each part of booms bears the gravity of front booms and concrete. It is the most dangerous working condition that all booms stretch out horizontally. Figure 4 shows concrete pump truck working site.

![Concrete pump truck working site](image1)

Fig 4. Concrete pump truck working site

Concrete pump truck boom system are constituted by several parts, and the total deflection is beyond 5% of its length. In this paper, we chose the first and second booms as research object, and other booms’ loads and gravity were loaded by equipment’s simulation vertically. Fig 5 shows the structure of the second arm.

![Specimen structure](image2)

Fig 5. Specimen structure

Concrete pump truck boom system experiment

Considering the large deflection in the loading progress, loading equipment cannot satisfy the deformation range of scale. So we chose only the first and second booms of boom system to conduct the experiments. And we compared the experiment results with the simulative results. The first, second booms and rotary base were assembled together, and then they were fixed on the test bench. Part structure of the third boom had been enhanced and assembled to the second boom, to make sure the boundary condition was same with the actual situation. Vertical stress was loaded on the third boom to make them bending. It is the simulation of the actual bending situation. Fig 6 shows the sketch of experiment.

![Sketch of concrete pump truck boom system experiment](image3)

Fig 6. Sketch of concrete pump truck boom system experiment
The gravity of boom system and concrete was defined as rated load. During the experiments, it is loaded by rate \( k \) gradually. Table 1 shows applying loads. All of bearing point loads, deformation of displacement and the strains of key part of boom system were recorded.

| Load rate \( k \) | 0.2 | 0.4 | 0.6 | 0.7 | 0.8 | 0.85 | 0.9 | 0.95 | 1 | \( \cdots \) | \( K_n \) | Till breakage |
|-----------------|-----|-----|-----|-----|-----|------|-----|------|---|-------|--------|---------------|

3.3 Establishment of the experiments
Concrete pump truck’s rotary base was fixed on high intensity test bench. Germanic IST experiment system was adopted to apply loads. Displacement sensor and load sensor were embedded in the hydraulic cylinder. The precision of load sensor is beyond 99.5%, and the range is 700kN. The precision of displacement sensor is beyond 99.5%, and the range is 850mm. The strain gauges on the specimen are 120Ω. All the experimental data transferred dynamically and wirelessly. Figure 7 shows the experimental system of booms’ buckling.

![Experimental system of booms’ buckling](image)

Fig 7. Experimental system of booms’ buckling

4. Example

4.1 Numerical calculation
Finite element analysis is the effective way to predict structure buckling. SE (2009) used the plate theory of two variable refined to take buckling analysis of plates. WB (2002) took post–buckling analysis imperfect stiffened laminated cylindrical shells under axial compression. In this paper we predicted the buckling positions and decided the test points by numerical calculation, and compared the numerical calculation to the experimental results in the whole process. Buckling load, form and the process between buckling and breakage of boom system were influenced by initial structure deformation, welding residual stress and initial flaws, which are related to manufacture factors. It cannot predict accurately because of randomness. So the influences of manufacture factors are not considered in simulation. Figure 8 shows the curve of material’s elastic-plastic characteristic, which can be obtained by tensile test.

![Stress-strain curve of steel](image)

Fig 8. Stress-strain curve of steel
Boom system’s load and boundary conditions were the same with bench experiment, which were gained by geometry nonlinear calculation. So buckling and post buckling deformation were acquired. Fig 9 shows boom system’s buckling calculation results and the corresponding boom experiment. Lower cover plate and side plate are prone to appear partial buckling instability, which presented as wave type buckling deformation. The lower cover plate of boom system supports bending stress. It started to present buckling deformation when load rate k reached 1.2. The side plate started to present buckling deformation when load rose, which was far less than material yield stress, so it was elastic deformation. It became plastic deformation when load rate k reached 1.75, and the calculation was not convergent. In the experiment, Strain gauges were set along axial direction from the initial buckling position to the end to measure deformation. Figure 9 shows positions of strain gauges, which were set on the side plate and lower cover plate.

Fig 9. Buckling calculation and corresponding strain gauges

4.2 Load-deflection
Figure 10 shows load rate k and deflection (f) curve during loading process. As we can see from the Figure, it was linear at the beginning, but deflection curvature dropped when load rate k exceeded 1.1, the curve begins to bifurcate. And deformation rate accelerated, which meant the structure buckling had occurred. When load rate k was beyond 1.7, the boom systems lost bearing capacity and structure breakage happened. The experiment value was basically fitted with analysis value. Destruction position was at the area of strain gauges, and finite element analysis was fitted with experiment results. Figure 11 shows position of buckling breakage.
4.3 Strain

Based on buckling experiment and analysis results, the lower cover plate started to appear buckling first. Figure 12 shows load rate k - strain ε curve at testing points. As is shown from Figure 12, strains were almost linear at each testing points in the initial stage. Strains changed dramatically when load rate k exceeded 1.1, and each strain curvatures of testing points were different. Figure 13 shows the lower cover plate of boom presented wave type deformation when k was beyond 1.1. Compared with experiment result curve with analysis curve, and it was more accurate during linear process than nonlinear process. And simulation analysis has much error and even be contrary to experiment results when structure in post buckling stage. The analysis load rate was 1.2, which was a little bigger than test value. As finite element model is ideal structure and specimen has initial flaws, so it is normal that experiment results are not in accord with simulation results.

Fig 12. Curves of experiments and simulations

Fig 13. Waveform of experiments and simulations

5. Conclusion

1) Concrete pump truck plates which take compressive stress occurred partial buckling instability easily, the lower cover plate and side plate present as wave type deformation. After buckling instability, there is no significant loss for structure bearing capacity and bearing limit is far more than critical instability load.

2) Geometry large deformation calculation has been proved by concrete pump truck boom system experiment. It is valid to predict boom system or other similar structure buckling deformation. It is precise and directive for product design in some way.

3) This paper provides a reference for analysis and experimental solution of construction machine boom system in the world.

References

[1] SE Kim, HT Thai and J Lee. Buckling analysis of plates using the two variable refined plate theory. Thin-Walled Structures 2009; 47:455-462.

[2] WB Yi, YF Luo, SHEN Hui shen, et al. Post–buckling analysis imperfect stiffened laminated cylindrical shells under axial compression. Journal of Tongji University 2002; 36:64-71.

[3] TL Wu, KK Shukla and JH Huang. Post-buckling analysis of functionally graded rectangular plates. Composite Structure. Composite Structure 2007; 81:1-10.

[4] Meisam Mohammadi, Ali Reza Saidi and Emad Jomehzadeh. Levy solution for buckling analysis of functionally graded rectangular plates. Applied Composite Materials 2010;
17:81-93.

[5] KS Na, JH Kim. Three-dimensional thermomechanical buckling analysis for functionally graded composite plates. Composite Structures 2006; 73: 413-422.

[6] YVS Kumar, JK Paik. Buckling analysis of cracked plates using hierarchical trigonometric functions. Thin-Walled Structures 2004; 42:687-700.

[7] C Bisagni, R Vescovini. Fast tool for buckling analysis and optimization of stiffened panels. Journal of Aircraft 2012; 46:2041-2053.

[8] SD Jiang, TG Cui. The application of concrete placing boom to concrete pump construction. Annals of the Rheumatic Diseases 2012; 71:1055-1063.

[9] M Broggi, GI Schueller. Efficient modeling of imperfections for buckling analysis of composite cylindrical shells. Engineering Structure 2011; 33:1796-1806.

[10] WG Carson, RE Newton. Plate buckling analysis using a fully compatible finite element. Aiaa Journal 2015; 7: 527-529.