The Critical Buckling Load of Column under Axial Compressive Force

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Abstract. Recent buckling failures of pipelines in permafrost regions reveal that buckling phenomenon is related to the initial displacement of the pipeline due to frost heave. The aim of this study is to investigate whether this relation influences widely the columns applied axial compressive forces. An apparatus was constructed to measure the loads applied on the specimens and the displacements of the specimens. The curve between the two measurement results are shown to lead to an accurate determination of the critical buckling load. Furthermore, a simulation calculation was conducted through finite element method, the numerical results are consistent with the experiment ones. We found that the critical buckling load is inversely correlated to the initial displacement, and further fitting the curves leads to a linear relation.

1. Introduction
Column-like members which are axially loaded, commonly compressively, are widely used in bridges, aircrafts, vehicles and other industries. Its stability problem has always been an important issue in the research field of machinery and engineering construction. Especially in the field of oil and gas transportation, several accidents of pipeline buckling, such as Canada’s Norman-well pipeline buckling accident, Uzbekistan’s Tashkent pipeline buckling accident and China’s Ge-la pipeline buckling accident, took place.

Because the transmission of oil requires a higher temperature, the temperature of the pipe wall during the operation period is higher than that during the construction period, and the temperature difference makes the pipeline expand. However, in the axial direction, the continuous expansion of hundreds or even thousands of kilometers of pipeline will cause serious damage: buckling instability. This kind of accidents have made scrapped, causing significant economic losses. According to the investigation of pipeline buckling accident, this kind of accident only occurred in permafrost area, but
never took place beyond permafrost area. Further investigations show that every pipeline buckling accident is accompanied by frost heave of soil around the pipeline. Therefore, it is necessary to study the frost heave and buckling of pipes. This kind of problem can be simplified as the buckling problem of compression bar with initial lateral displacement.

The buckling analytical solution of axially compressed structure was given by Euler in 1744, which preliminarily solved the instability problem of fixed length members\(^1\). Similar research also includes the empirical formula of the relationship between the length and strength of column members proposed by Musschenbroek\(^2\). With the emergence of the buckling problem of railway and pipeline, Martinet proposed the infinite beam model of winkle foundation, and T. Allan’s experiment studied the buckling of thin steel sheet\(^{3-6}\). Although these studies promote the understanding of buckling phenomenon to a certain extent, they have great limitations for the buckling of pipes, and fail to solve the nonlinear problems of buckling itself and pipe soil interaction. Musschenbroek ignored the influence of specimen length, and the model of martinet and T. Allan is over simplified, which may lead to a large error with the actual results. With the development of finite element method, the effects of phase transformation characteristics, different constraints, initial geometric defects and load changes on buckling are gradually recognized\(^{7-8}\). In the field of petroleum engineering, the buckling studies of sucker rods and pipelines with different materials and working conditions were completed by Yang Meihua, Zhang Xiao, Felipe Franzoni, Falk, etc\(^{9-12}\). With an analysis of the public literatures, it is found that there is a lack of test results to verify the simulation study. Given the facts above, this paper investigates the relationship between the initial lateral displacement and the critical buckling load, and carries out small scale test research of buckling.

2. Experiment

Therefore, it is necessary to study the frost heave and buckling of pipes. This kind of problem can be simplified as the buckling problem of compression bar with initial lateral displacement.

2.1. Apparatus

The experimental apparatus is constructed based on the traditional mechanical test. The initial lateral displacement of the test piece is realized by the middle part of the test piece with the vertical jacking rod with thread. The device is fixed on the stand column of the workbench. The jacking rod and the base of the device are connected by thread. The thread pitch is 1mm. The initial lateral displacement obtained by the test piece is determined by recording the rotation cycles of the jacking rod.

![Figure 2. Schematic and photo of the experimental system](image)

In Figure 2. (1), \(a\) is the initial displacement, \(P\) is the load applied axial on the specimen. After the initial displacement \(a\) is generated, the axial load \(P\) of the specimen is applied, and the displacement and load changes are measured at the same time. According to the curve between the displacement and the load applied, the critical buckling load is determined, and the relationship between the critical buckling load and the initial lateral displacement is analyzed.
The specimens are straight steel bar with circular cross section, 1 m long and 10 mm in diameter. Defects caused by material are not considered, such as possible micro tissue defects inside.

The specimens are divided into four groups, each group consists of six ones which are applied to the same initial lateral displacement, the values of the initial lateral displacements are 3mm, 5mm, 7mm and 9mm respectively.

2.2 Experiment results
According to the displacement-load curve based on the test results, the process of loading roughly reveals two stages: the first is the stage of rapid increasing of the load and the second is the stage of buckling. In the former stage, the load increases rapidly, however, the displacement increase slowly; on the contrary, the load in the latter stage decreases gradually after reaching the maximum, but the displacement increases rapidly, indicating that the specimen has buckled. According to the displacement-load curves in Figure 3, all the specimens buckled except for two specimens, and the post buckling load decreased dramatically. The curve of two abnormal test pieces shows that the load starts to decrease immediately after loading, but the displacement increases continuously. This phenomenon is due to the instability of high-pressure oil pump and occasional short-term loss of pressure. Therefore, when the results of buckling critical loads are calculated, the data of two obviously abnormal specimens are ignored.

![Figure 3. Curves of displacement-load in experiment results](image)

(1) a=3mm; (2) a=5mm; (3) a=7mm; (4) a=9mm

2.3 Result Analysis
The displacement-load curves of each group are compared, and the results are shown in Figure 1. The critical buckling load of each specimen is the highest point of displacement load curve, that is, the point where the load takes the maximum value.

In order to further analyze the relationship between the critical load and the initial lateral displacement and eliminate the accidental error, the average value of critical buckling load of each group of test pieces is calculated, and the results are shown in Table 1.
Table 1. Critical buckling load of specimens

| Number of group | Initial Displacement (mm) | 1  | 2  | 3  | 4  | 5  | 6  | Average |
|-----------------|---------------------------|----|----|----|----|----|----|---------|
| 1               | 3                         | 3.65 | 6.35 | 6.7 | 6.7 | 6.5 | 6.15 | 6.5     |
| 2               | 5                         | 5.5  | 6.6  | 5.75 | 6.8 | 6.3 | 6.3 | 6.31    |
| 3               | 7                         | 6.3  | 5.7  | 5.8  | 6.1 | 6   | 0.8  | 5.73    |
| 4               | 9                         | 5.55 | 4.75 | 4.85 | 5.65 | 5.9 | 5.65 | 5.44    |

Based on the results of the above table, the fitting curve between the initial lateral displacement (geometric imperfection) and the critical buckling load is determined.

3. Numerical simulation

Through the establishment of the finite element model with the same size as the test specimen, the simulation analysis is carried out.

3.1 The model

The model is established with the beam188 element. The diameter of the simulation specimen is 1cm, and the material is steel. The specific parameters are shown in Table 2.

Table 2. The parameters of the model

| Element      | Cross section | Prxy(Pa) | ex  | R   | N   | T   |
|--------------|---------------|----------|-----|-----|-----|-----|
| Beam188      | csolid        | 2.06e11  | 0.3 | 10  | 16  | 4   |

The applied load in the simulation analysis refers to the test load. The maximum value of the buckling critical load in the four groups of specimens is 6.7kN, and the setting of the simulation analysis load is 7kN, slightly higher than the maximum value of the test.

3.2 Numerical results

Figure 4 shows the comparison between the test and simulated buckling critical load when the lateral initial displacement $a = 7$mm. The blue curve is the experimental result and the red curve is the simulation result.

![Figure 4. Critical buckling load comparison of experiment and simulation](image)

Comparing with the curves in the above figure, it is found that the curve trend of test results is similar with the simulation results, and the two curves have good consistency. According to the data of each group, as shown in Table 3, the maximum relative error is 8.3%.

Table 3. Relative errors between experiment and simulation results

| Initial displacement a(mm) | Experimental load (kN) | Load in simulation (kN) | Error between experiment and simulation |
|----------------------------|------------------------|-------------------------|----------------------------------------|

4. Conclusions
The experimental and simulated displacement responses of specimens with initial lateral displacement show that the smaller the initial lateral displacement is, the larger the curvature of displacement curve changes. There is a significant correlation between the initial lateral displacement and the critical buckling load. The larger the initial lateral displacement is, the smaller the critical buckling load is. The gap between the simulation results and the test results is less than 10%, which shows that the simulation results confirm the test results.

Acknowledgement
The study was supported by the research plan of Hebei province (The critical buckling load of column applied compressive force:172176431)

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