Displacement-based Mode Pushover Analysis of Self-anchored Cable-stayed Suspension Bridge

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ABSTRACT

As being a typical multi-freedom degree system structure, self-anchored cable-stayed suspension bridge is significantly affected by higher modes in the earthquake response. Traditional force-based pushover analysis of reverse triangle or uniform distribution patterns will lead to a certain error for the results of pushover analysis of self-anchored cable-stayed suspension bridge. An improved method of displacement-based mode pushover analysis is presented in this paper by combining the two stage horizontal displacement pattern with mode pushover. This improved method can take the contributions of higher modes into account. And the applicability of the method can be verified commendably by the selected examples.

Traditional force-based pushover analysis considers the seismic load is equivalent to lateral load. And it judges whether the deformation ability of the structure and component can meet the need of design and use function by analysing nonlinear response of structures under the monotonic increasing horizontal lateral load applied to the structure with a certain distribution mode. The selection of the lateral load distribution mode can directly affect the analysis results of the pushover method on the seismic performance of whole structure in traditional force-based pushover analysis. Moreover, the problem of stiffness degradation after failure is not taken into account in this traditional wide application method. Seismic hazard, experiment and theoretical analysis indicate structural collapse is mainly due to the lack of deformation capacity and energy dissipation capacity during severer earthquake. In this case, the deformation capacity and the displacement response of structure will have an certain impact on the damage degree of structural members. Therefore, it is more reasonable to use displacement control on structural seismic response during severer earthquake[4].

Compared with the traditional force-based design, the displacement of structure can reflect the nonlinear reactive state more during severer earthquake, it also can control the behavior of structure better in earthquake. Consequently, the displacement-based seismic design method has been greatly developed[5-10]. There are three commonly used displacement-based seismic design method: ductility factor design, capacity spectrum and direct displacement-based design method. The
The basic thought of displacement-based mode pushover analysis is as follows: first, put monotonic increasing lateral displacement to bear on structure directly according to a certain horizontal displacement distribution mode, second, the final failure pattern of structure is obtained by pushover the structure to the target displacement, after that, whether the deformation ability of structure and component can meet the need of design and use function can be analyzed.

EQUIVALENT SINGLE DEGREE FREEDOM SYSTEM BASED ON HORIZONTAL DISPLACEMENT MODE

One of the basic assumptions of pushover analysis is equivalent actual multi-freedom degree system to a single degree freedom system. The equivalent process in the improved method is based on the displacement mode, which shows the rationality of the static displacement-based pushover analysis.

The dynamic equation of multi-freedom degree system under earthquake is as follows:

\[
[M]\{\ddot{y}\} + [C]\{\dot{y}\} + \{F(y)\} = -[M]\{1\} \dot{y}_0 \tag{1}
\]

For the bridge structure, \(\{\dot{y}\}\) can be expressed by vertex displacement \(y_i\) and displacement shape vector \(\{u\}\), \(\{y\} = \{u\} y_i\), \(\{u\}\) is the displacement mode studied in this paper, so formula 1 can be written as follows:

\[
[M]\{u\} \ddot{y}_i + [C]\{u\} \dot{y}_i + \{F(y)\} = -[M]\{1\} \dot{y}_0 \tag{2}
\]

Multiply both sides by \(\{u\}^T\), it can draw a formula:

\[
\{y\} = \frac{\{u\}^T [M]\{1\}}{\{u\}^T [M]\{u\}} y_e \tag{4}
\]

Formula 3 becomes the following:

\[
\{y\} = \frac{\{u\}^T [M]\{u\}}{\{u\}^T [M]\{1\}} y_e \tag{5}
\]

Equivalent displacement

\[
y_e = \frac{\{u\}^T [M]\{u\}}{\{u\}^T [M]\{1\}} y_i \tag{6}
\]

Equivalent mass

\[
M_e = \{u\}^T [M] \{1\} \tag{7}
\]

Equivalent damping

\[
C_e = \{u\}^T [C] \frac{\{u\}^T [M]\{1\}}{\{u\}^T [M]\{u\}} \tag{8}
\]

Equivalent restoring force

\[
F_e = \{u\}^T \{F(y)\} \tag{9}
\]

The dynamic equation of equivalent single degree freedom system is obtained:

\[
M_e \ddot{y}_e + C_e \dot{y}_e + F_e = -M_e \dot{y}_0 \tag{10}
\]
The above is the derivation process based on displacement mode (displacement shape vector \( \{u\} \)) of equivalent single degree freedom. The derivation process states clearly that displacement-based pushover analysis of equivalent single degree freedom system is theoretically reliable in displacement-based seismic design.

**THE SPECIFIC IDEAS OF DISPLACEMENT-BASED MODE PUSHOVER ANALYSIS**

Double control method is utilized to determine the number of involved vibration type, and the selected K vibration types are analyzed by pushover method in order to obtain the pushover curve of each involved vibration type. Second, adopting two stage displacement loading mode on vibration types with pushover curve has a plastic stage, the elastic displacement shape vector is used before yielding, and the yield time displacement of the pier is taken as the displacement shape vector after yielding. Furthermore, one stage displacement loading mode is used to vibration types with pushover curve has only elastic stage. In summary, it is the improved method of displacement-based mode pushover analysis.

**EXAMPLE**

**Profiles of Zhuanghe Construction Bridge**

Zhuanghe Construction Bridge, the world's first concrete self-anchored cable-stayed suspension bridge. The span is 41.6+100+41.6 = 183.2 meters. The main beam is concrete solid edge girder, 28.6 meters wide. Seismic fortification intensity of the bridge is VII degree.

**Finite Element Model**

Space finite element analysis is selected for analyzing seismic response of bridge. As for self-anchored cable-stayed suspension bridge, the main work in establishing finite element model of dynamic analysis is to simulate the quality and stiffness of main beam, main tower, cable, pier and foundation of the bridge, furthermore to simulate the conditions of the border. Finite element model of the bridge is shown in Figure 1.

![Figure 1. Finite element model of Zhuanghe Construction Bridge.](image1)

![Figure 2. Plastic hinges distribution obtained by time history analysis.](image2)
Nonlinear Seismic Response Analysis

Take 1940 El Centro wave as the input ground motion along the longitudinal direction of the bridge. Adjust peak acceleration to 0.4g to ensure structure goes into the elastic phase. The structural damping ratio is 3%. Nonlinear time history analysis is used to get the maximum longitudinal displacement of top tower is 0.2904m and the maximum longitudinal displacement of main span is 0.2822m simultaneously.

The plastic hinge deformation history curve of time history analysis can be seen that 100, 101, 102 units yield forming plastic hinge, in which 100 (200), 101 (201) units form a complete loop, their rotary deformation are between yield displacement and ultimate displacement. This case illustrates the structure has not yet reached the ultimate failure although there is damage. At the same time, the position of plastic hinge on tower in the symmetrical structure and rotary deformation of the plastic hinge is completely symmetrical, the plastic hinge distribution on tower of cooperative system as shown in Figure 2.

Pushover Analysis

On the basis of modal analysis on Zhuanghe Construction Bridge, the basic cycle and vibration types are obtained. Double control method is utilized to determine the number of involved vibration type, and K longitudinal vibration types are selected for analysis by improved mode pushover method based on displacement.

Taking the girder center point as the displacement control point, the target displacement of structure is calculated according to the formula $\mu_{ro} = 0.311 m$. The pushover curve of Zhuanghe Construction Bridge and plastic hinge in the sequence as shown in Figure 3, 100 (180), 101 (181), 102 (182) are number of units for forming plastic hinges, the plastic hinge position as shown in Figure 4.

Comparison of Calculation Results

The calculated results are compared between improved method of displacement-based mode pushover analysis with the nonlinear time history analysis. Two pushover curves are shown in Figure 5, it can be seen that the
pushover curve with improved method of displacement-based mode pushover analysis is closed to the curve of nonlinear time history analysis. The two curves are basically consistent especially before yielding.

![Comparison of pushover curve](image)

**Figure 5.** Comparison of pushover curve.

**CONCLUSION**

This paper has conducted a improved method of displacement-based mode pushover analysis on self-anchored cable-stayed suspension bridge, the method take the contributions of higher modes and vibration characteristics change after yielding into account and without not convergent situation in pushover analysis due to horizontal displacement mode loading. The improved method summed up in this paper can be used as performance evaluation for the Zhuanghe Construction Bridge and other similar bridges.

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