

# Seismic Ductility Capacity Research of Integral Building-Bridge Station Structure

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**Abstract:** The performance-based structural design requires that the structure has a clear structural performance target under the specified set-up criteria, and the performance target is specifically reflected in the structural damage degree. This paper analyzes in detail the strength criteria of structural failure. Combined with the actual bridge-building project, the dynamic elasto-plastic analysis of the fiber unit is used to obtain the transverse and longitudinal ductility of the structure. Being destroyed, the displacement of the structure and the study of energy dissipation failures have been carried out. It is known from the research that the ductility of the analyzed engineering structures is good and meets the requirements of the current specifications, and can be used as a useful reference for structural seismic design.

## 1. Introduction

With the development of technology, the design of bridges at this stage often adopts a seismic design method based on ductility, and the nonlinear dynamic response of the structure subjected to earthquakes is used as the research basis. By analyzing the appearance of plastic hinges when the structure is unstable or collapsed, development and distribution status, rational design of the structure <sup>[1]</sup>, we can improve its ultimate deformation capacity and hysteretic energy performance.

In order to ensure the reasonable strength and inflammatory property of the whole structure, the ductile design method<sup>[2]</sup> often consumes input energy through local deformation of the member.

## 2. Structural failure criteria

### 2.1. Strength failure criteria

The failure criterion of the structure which was first proposed and the most applied is the strength failure criterion <sup>[3]</sup>. This criterion is simple and easy to apply. In the structural design, both the allowable stress method and the bearing capacity limit state design method are widely used. However, from the angle of earthquake resistance, this criterion is too singular and therefore not fully adapted to the seismic design of the structure. For the seismic design of the structure, from the perspective of economic efficiency, a certain elastoplastic deformation is usually allowed, and the structure under strong earthquake has almost no strength reserve, and the strength failure criterion is no longer applicable.

### 2.2. Deformation and damage criteria

The deformation failure criterion requires that the maximum displacement of the structure should be



lower than the allowable displacement value, expressed as follows <sup>[4]</sup>:

$$\Delta_{\max} \leq [\Delta] \quad (1)$$

among them,  $\Delta_{\max}$  is the maximum displacement value,  $[\Delta]$  is the allow values for displacement.

Equation (1) can also be expressed as:

$$\mu_{\Delta} \leq [\mu_{\Delta}] \quad (2)$$

among them,  $\mu_{\Delta}$  for the maximum displacement ductility value under earthquake action,  $[\mu_{\Delta}]$  is the allowable displacement ductility factor.,

When the seismic design of the structure adopts the deformation failure criterion<sup>[5]</sup>, the structural performance under strong earthquake is closely related to the inelastic deformation ability. From the deformation, the damage of the structure under earthquake is divided into: the displacement exceeds its own deformation ability, and the damage of the strength and stiffness rapidly reduce, which is called "one-time transcendence"; the damage of the structure under cumulative damage and low-cycle fatigue, which is called "Repeated damage type."

### 2.3. Energy damage criteria

The energy failure criterion <sup>[6]</sup> applied to structural seismic design was first proposed by Housner et al., based on the fact that the dynamic response of the structure is repeated multiple times below the amplitude of one transcendence under strong earthquakes, and finally due to accumulation. Finally, the damage occurs because the accumulated hysteresis energy exceeds the allowable deformation energy.

$$E_h = [E_h] \quad (3)$$

In the formula,  $E_h$  is accumulated hysteresis energy,  $[E_h]$  is the allow deformation to consume energy.

Considering structural seismic performance from an energy perspective has a clear physical meaning. However, the energy destruction criterion is difficult to apply in practical engineering , because  $E_h$  and  $[E_h]$  are not easy to be determined.

### 2.4. Deformation and energy double damage criteria

The double failure criterion is that the damage of the structure is caused by the combination of deformation and cumulative energy consumption. Park and Ang <sup>[7]</sup>proposed a representative double failure criterion:

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u Q_y} \int dE_h \quad (4)$$

In the single degree of freedom system:  $D$  is the system damage indicators;  $\delta_m$  is the maximum displacement under earthquake;  $\delta_u$  is the ultimate displacement of the system;  $\int dE_h$  is the total hysteretic energy consumption of the system during the ground motion time history;  $Q_y$  is the yield strength of the system;  $\beta$  is the system parameter.

In the multi-degree of freedom system:  $D$  is the damage index of a unit; the other parameters are the same as the single degree of freedom system.

In theory, for reinforced concrete structures, the double failure criterion is more adaptive, because the cumulative damage is also considered while considering the maximum deformation.

### 2.5. Low cycle fatigue failure criteria

Under repeated loading <sup>[8]</sup>, the structure will produce irreversible damage and damage will occur as the

damage accumulates. This process is called structural “fatigue”. When determining the damage of a structure subjected to a reciprocating load, it is assumed that the damage of the structure complies with the linear accumulation rule, namely:

$$\sum_{i=1}^n \frac{n_i}{N_i} = 1 \quad (5)$$

In the formula,  $N_i$  is the cycles number of the stress level  $S_i$  in the failure, and  $n_i$  is the cycles number of the actual applied stress level  $S_i$ . For the low-cycle fatigue problem, considering the modified Miner criterion proposed by Chung and Mayer et al., the damage value is:

$$D = \sum_i a_i^+ \frac{n_i^+}{N_i^+} + a_i^- \frac{n_i^-}{N_i^-} \quad (6)$$

In the formula,  $N_i^+$  and  $N_i^-$  are the corresponding fatigue life of the displacement level  $\delta_i^+$ ;  $n_i^+$  and  $n_i^-$  are the number of load cycles actually applied;  $a_i^+$  and  $a_i^-$  are the damage correction coefficient (the sign indicates its loading direction).

### 3. Elastoplastic fiber model

#### 3.1 Principle of fiber model

The section of a beam element is divided into a plurality of fiber models, and only the axial deformation of the model is considered in the analysis. Such a model is called a fiber unit<sup>[9]</sup>.

The fiber model uses the following assumptions:

- (1) The section maintains a flat section deformation and is perpendicular to the axis of the member;
- (2) The slip between steel and concrete is not considered
- (3) The line connecting the centroids of the beam unit is a straight line.

In the fiber model, the axial deformation corresponds to the axial deformation of the section, the strain of the fiber determines the fiber stress, and the stress of the fiber calculates the bending moment and the axial force. The relationship between the two is:

$$\varepsilon_i(x, y, z) = [H] \{d(x)\} \quad (7)$$

Among them  $\{d(x)\} = [\phi_y(x), \phi_z(x), \varepsilon_o(x)]^T$  is the deformed column vector at the coordinate  $x$  on the section;  $[H] = [-z_i y_i 1]$  is the amount of linear geometric transformation;  $\phi_y(x)$  is the curvature of the  $y$  axis of the section element coordinate at the axial direction  $x$  of the beam element;  $\phi_z(x)$  is the curvature of the  $z$ -axis of the section element coordinate at the axial direction  $x$  of the beam element;  $\varepsilon_x(x)$  is the axial strain of the beam element at the axial  $x$  section;  $y_i$  is the position of the fiber  $i$  on the section;  $z_i$  is the position of the fiber  $i$  on the section;  $\varepsilon_i$  is the strain of fiber  $i$ .

The stress of the corresponding fiber is:

$$\sigma_i(x, y, z) = E(x, y, z) \varepsilon(x_i, y_i, z_i) \quad (8)$$

Among them  $E(x, y, z)$  is the elasticity modulus of the fiber in the cross section  $(x, y, z)$ , taking the integral of the section, the force on the section is:

$$\{q(x)\} = [k_s(x)] \{d(x)\} \quad (9)$$

Among them,  $\{q(x)\} = [m_y(x), m_z(x), p_0(x)]^T$ ,  $m_y(x)$ ,  $m_z(x)$ ,  $p_0(x)$  are the bending

moment and the axial force around the y and z axes on the section. Then the unit section stiffness matrix is:

$$[k_s(x)] = \int_A [H]^T E(x, y, z) [H] dydz \quad (10)$$

Correspondingly, the flexibility matrix of the unit section is:

$$[f_s(x)] = [k_s(x)]^{-1} \quad (11)$$

Dividing the beam-column unit established by the elastoplastic fiber model into several small segments, and the features of the segment are represented by the middle section of each segment.

#### 4. Project Overview

In the second phase of Qingdao Hongdao-Jiaonan Intercity Railway is a typical island-type station structure, which adopts the Integral Building-Bridge frame structure. The total length of the station is 126 m (main body 85 m, attached 41 m). The seismic fortification category is the key fortification category, 7 degree fortification intensity, the design earthquake group is the third group, the class II site category, the characteristic period is 0.45 s, and the seismic rating is level 2.

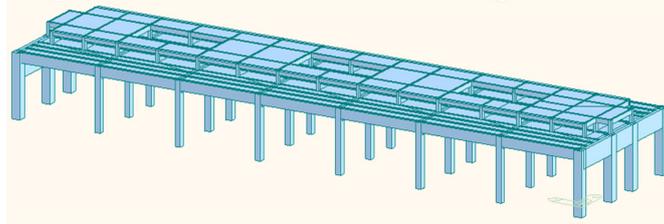


Fig.1 Finite element model

1 layer height of the structure is 7.65 m, and the 2 layer height is 1.6 m. The beam, column and plate (simulated by rigid plate) are composed of three component units. The model consists of 358 nodes, 572 beam units, and 279 plate units.

In structural elastoplastic analysis, plastic hinges usually appear on some components of the structure, such as the frame beam of the frame structure, the column, and the pier of the bridge structure. Therefore, for the sake of convenience, when input the reinforcement of the member, the plastic hinges that appear on the frame beam, the column and the frame beam are considered, the plastic hinges that appear on the secondary beam with the ground motion are not considered.

#### 5. Ductility performance of longitudinal bridge

In the Integral Building-Bridge structure, because the longitudinal beam has a restraining effect on the pier, the finite element software is used to establish the overall structural model, the static push method is used to obtain the yield displacement of the pier column, and the elastoplastic dynamic time history analysis is used to obtain the Corresponding maximum nonlinear displacement of pier column. The fiber model is used to check the ductility of the pier under the action of large earthquakes. The hysteresis curve is used to describe the energy consumption. The area enclosed by the curve indicates the equivalent damping effect of the section after plastic hinge. At the same time, the strength of energy consumption of the section can be qualitatively explained.; the stress state of the material in the fiber distribution diagram can indicate the damage of the entire section.

##### 5.1. Calculation of displacement

The dynamic elastoplastic analysis based on fiber unit is carried out for the Integral Building-Bridge structure, the yield displacement and maximum displacement of each type of pier are obtained, calculating displacement ductility ratio, as is shown in Table 1.

Table 1 Displacement ductility ratio along the bridge

pier column	yield displacement (cm)	Max displacement (cm)	yield displacement/Max displacement
KL1	1.639	4.448	2.714
KL2	1.899	4.465	2.351
KL3	1.778	4.468	2.513
KL4	1.908	4.478	2.347

It can be seen from Table 1 that the longitudinal stiffness of the pier column meets the requirements of the displacement ductility ratio limit of 4.8 in the Code for Seismic Design of Railway Engineering.

### 5.2. Energy consumption and damage state

According to the calculated curve of the bending angle of the structure, it can be seen that when the structure enters the elastoplastic state, the area surrounded by the bending angle hysteresis curve of the control section of each column is relatively large, and when the control section does not enter the yielding state, the bending angle hysteresis curve is an S-shaped curve, indicating that the energy consumption of the section entering the elastoplastic stage is higher. The area surrounded by the bending angle hysteresis curve of the bottom sections of KZ1 and KZ2 is larger than the area enclosed by the top section, indicating that the equivalent damping effect of the bottom section is larger than that of the top section. The area enclosed by the bending angle of the top and bottom sections of KZ3 and KZ4 is equivalent, indicating that the equivalent damping effect is equivalent. The cross-sectional damage state is closely related to the material strain relationship.

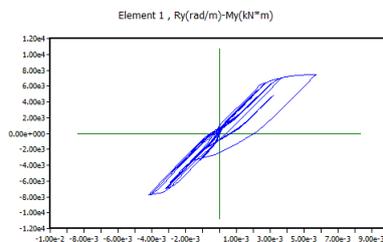


Fig. 2 bottom section bending moment of KZ1



Fig.3 bottom section fiber distribution of KZ1

## 6. Ductility performance of transverse bridge

### 6.1. Checking the displacement

By Table 2 can be known that the ductility of the pier-crossing bridge meets the requirements of the displacement ductility ratio limit of 4.8 in the Code for Seismic Design of Railway Engineering.

### 6.2. Energy consumption and damage state

It can be seen from the bending angle curve that the area surrounded by the bending angle hysteresis curve of the KZ1 and KZ2 bottom sections is larger than the area enclosed by the top section, indicating that the equivalent damping effect of the bottom section is larger than the top section. The area enclosed by the bending angle of the top and bottom sections of KZ3 and KZ4 is equivalent, indicating that the equivalent damping effect is equivalent. It can be seen from the fiber distribution that the more the number of reinforcing bars entering the yielding stage, the larger the area surrounded by the hysteresis

curve, indicating that the equivalent damping of the reinforcing steel after the section enters the yielding stage is obvious. The steel in the tension zone is elastic before the cross-section yields, and after the cross-section yields, the steel in the tension zone also yields. The cross-sectional damage state is closely related to the material strain relationship.

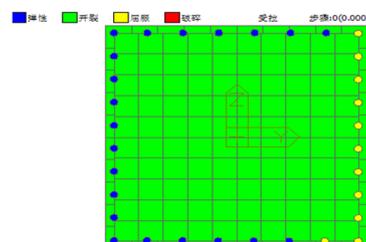
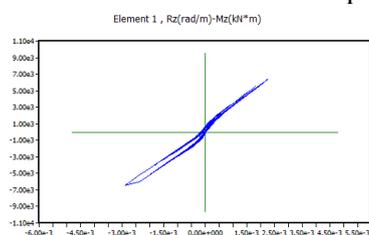


Fig.4 bending angle of bottom section 1 of KZ1

Fig.5 bottom section fiber distribution of KZ1

## 7. Summary of this chapter

Based on the fiber element model, this paper analyzes the seismic ductility of the structure and conducts dynamic elastoplastic analysis of the actual integral building-bridge structure.

(1) The longitudinal and lateral displacements of the structure of the bridge-building elevated station are all in accordance with the current specifications.

(2) The steel bar in the tension zone of the station column is elastic before the section is yielded. After the section yields, the steel in the tension zone also yields.

(3) The equivalent damping effect of the bottom section of the pier column is greater than the top section.

(4) The ductility of the pier column meets the requirements of the specification.

(5) The size of the surrounding area of the hysteresis curve depends on the number of steel bars that enter the yield. If the number of yielding bars is large, the surrounding area is large. If there is no steel bar entering the yield, the hysteresis curve is an S curve, indicating that the magnitude of the equivalent damping effect depends primarily on the reinforcement, after the section becomes plastic hinged.

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