Analysis on Seismic Damage Evolution of Seismic-Damaged CSC Columns with Strengthening

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Abstract. To analysis the earthquake damage evolution law, seven composite steel concrete (CSC) columns were manufactured. The experiment consisted of pre-damage loading, reinforcement with enveloped steel jackets (ESJ)/CFRPs and pseudo-static tests. The results showed that the severely damaged specimens strengthened with CFRPs or ESJ have the ability to resist earthquake again. The experimental results were in good agreement with the analytical results. Based on the modification and extension of Reihorn evaluation criterion, the earthquake damage evaluation criterion of seismic-damaged CSC columns with strengthening was obtained, which describes the specimen from “basically intact” to “complete destroyed”. Then, the seismic damage evolution law of specimen was obtained by quantitative analysis of the test results.

Keywords: seismic-damaged; composite steel-concrete (CSC) columns; earthquake damage evolution law; pseudo-static tests; evaluation criterion

1. Introduction

The existing buildings, bridges and airports subjected to extreme loads such as earthquakes, typical winds and explosions are very easy to be irreversibly injured and destroyed, resulting in a great amount of casualties and economic losses in the affected areas [1].

The types of seismic damage models were different when the types of structural systems were different. Niu et al. modified and improved the Park-Ang model based on the actual situation in China [2]. In 1978, Park and Ang proposed the seismic damage model of RC members [3]. Kunnath et al. [4] modified the Park-Ang model to solve the problem of unreasonable value range, however, the influence of built-in steel has not been taken into consideration of the energy dissipation factor, \( \beta \). Chai et al. [5] replaced the energy dissipation factor, \( \beta \), by the modified energy dissipation factor, \( \beta^* \), to obtain the seismic damage model of seismic-damaged RC structures. Liu et al. [6] determined the calculation formula of energy dissipation factor, \( \beta^* \), and obtained the seismic damage model suitable for CSC column, but it could not solve the damage problem of seismic-damaged CSC structure with strengthening. It has become an important content to establish the seismic damage model of seismic-damaged CSC columns with strengthening and to research the earthquake damage evolution law.

Hence, seven CSC frame column test models were constructed, and pre-damage loading, ESJ reinforcement, CFRPs reinforcement and pseudo-static loading were carried out, and the earthquake damage evolution law of seismic damaged columns under the two reinforcement methods was analyzed.
2. Experimental Design
To simulate the behavior of CSC frame columns under earthquake action more realistic, the bottom column of plane frame was taken as the research object. Based on the existing specifications, seven CSC frame column test models were designed and manufactured. The rectangle cross section and effective height were 200 mm×270 mm and 1570mm respectively. The four corners of the rectangle cross section of the column were 4ϕ16 longitudinal bars, and the stirrups were ϕ8@100. The steel ratio, ρa, longitudinal reinforcement ratio, ρl, and stirrup ratio, ρv, were 4.84%, 1.6% and 0.68%, respectively. The concrete cover was 25mm, and the average compressive strength of the concrete cube was 39.6 Mpa. Other performance parameters, test device and loading system, design and measurement contents of CFRPs and ESJ strengthened column were all referred to reference [7-8].

3. Seismic Damage Model

3.1. Definition and Properties of Damage Index
Damage index was usually represented by D, whose value is between [0, 1]. Damage was an irreversible process [9]. Based on the failure mechanism of the structure in earthquake, it is more helpful to quantify the earthquake damage.

3.2. Double-parameter damage model
The double-parameter model proposed by Park-Ang [5], which was widely recognized by peers.

\[
D5 = \delta_m + \beta_0 \frac{E_u}{F_s} \delta_u
\]  

where \( \delta_m \) is the maximum deformation and \( \beta_0 \) is the energy dissipation coefficient. \( \lambda \) is the shear span ratio of the section column.

Based on Park-Ang model, after considering the effect of loading path, a brand-new model was put forward by Wang et al. [10].

\[
D7 = (1 - \beta_1) \left( \delta_m - \delta_y \right) + \beta_0 \sum \frac{E_i}{F_s} \delta_i
\]  

Based on Eq. (3), Liu et al. [10] proposed the calculation formula of energy dissipation coefficient for CSC structure considering steel ratio, shear span ratio and stirrup ratio as follows:

\[
\beta_1 = -0.002 \rho_a + 0.005 \lambda + 0.01 \rho_v
\]  

Sun et al. [11] used the material performance reduction method to analyze the seismic damage components, and compared with the experimental results to verify its effectiveness.

\[
D8 = (1 - \beta_1) \left( \delta_m - \delta_y \right) + \beta_1 \sum \frac{E_i}{F_s} \delta_i
\]  

In 1995, Chai et al. [5] established a modified energy dissipation factor, \( \beta^* \), formula which can use seismic pre-damage to solve the shortcomings of Park-Ang model.

\[
D9 = \delta_m + \beta^* \frac{E_u}{F_s} \delta_u
\]

\[
\frac{\beta^*}{\beta_0} = \frac{\mu_m}{\mu_m + (1 - \mu_m) \beta_0}
\]
where $\beta^*$ is the modified energy dissipation factor of seismic-damaged RC structural component. $\mu_{si} = \delta_i/\delta_y$.

4. Seismic Damage Model of Seismic-Damaged CSC Columns with Strengthening

4.1. Damage Accumulation Curve

The cumulative damage curves of double-parameter damage model were obtained by substituting the test results into Eq. (1) to Eq. (7), as shown in figure 1.

$$\mu_{si} = \left| \frac{\delta_i}{\delta_y} \right|$$

where $\mu_{si}$ is the ductility coefficient of the $i$-th load half cycle.

![Cumulative damage curves of double-parameter model.](image)

Figure 1. Cumulative damage curves of double-parameter model.

4.2. Proposed of Seismic Damage Model
Equation (5) of Sun et al. model was applicable to the CFRPs-strengthened or ESJ-strengthened seismic-damaged CSC frame column. Hence, the seismic damage model suitable for seismic-damaged CSC frame column with strengthening can be described as follows:

\[ D = (1 - \beta) \left( \frac{\delta_u - \delta_y}{\delta_y} \right) + \beta \frac{\sum F_i}{E} \left( \frac{\delta_u - \delta_y}{\delta_y} \right) \]  

(9)

\[ \beta = -0.002 \rho_u + 0.005 \lambda + 0.01 \rho_u \]  

(10)

Table 1 shows the damage variable $D$. The mean ratio, standard deviation, coefficient of variation are 0.917, 0.0601 and 0.0663, respectively.

| Specimen  | SRC-0 | SRC-1 | SRC-2 | SRC-3 | WSRC-0 | WSRC-1 | WSRC-2 |
|-----------|-------|-------|-------|-------|--------|--------|--------|
| Damage index | 0.86  | 0.83  | 0.89  | 0.91  | 1.04   | 0.96   | 0.93   |

4.3. Damage quantification of experimental results

In 1992, Reihorn et al. [12] put forward the evaluation criteria for research the damage of RC structures. In order to obtain the evaluation criteria of seismic-damaged CSC frame column with strengthening, Reihorn’s evaluation criteria was further modified and extended, as shown in table 2.

| Damage degree  | Damage value | Damage state  | Experimental phenomenon                                                                                                                                 |
|----------------|--------------|---------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| Basically intact | 0 to 0.1    | Undamaged     | The deformation of the column is small, no cracks in the concrete, no deformation in the CFRPs and the ESJ.                                               |
| Slightly damage | 0.1 to 0.3   | Mild injure   | The concrete cracked, CFRPs slightly buckled, and no obvious deformation in the ESJ.                                                                   |
| Moderately damage | 0.3 to 0.7 | Repairable    | Cross oblique cracks appears at the column, the web of steel is partially yield, CFRPs bulge is obvious.                                               |
| Severe damage   | 0.7 to 0.9   | Unmodifiable  | The web of steel and stirrups are yield, CFRP bulges and fractures, and the part of the welded joint between batten plate and angle steel basically ruptured. |
| Collapse        | 0.9 to 1.0   | Completely fractured | The bearing capacity decreases sharply, CFRPs completely fractured, most of the welded joint basically ruptured, and ESJ completely fractured. |

According to the evaluation criteria given in table 2, the damage quantification of the experimental results was carried out, as shown in figure 2.
Figure 2. Damage quantification of specimens

5. Conclusion

(1) After strengthened with CFRPs, the hysteretic loops of the severely damaged specimens were plump, and the ductility and energy dissipation properties were significantly increased, showing the ability to resist earthquake again.

(2) The results revealed that the severely damaged specimens strengthened with CFRPs or ESJ had the ability to resist earthquake again, and their seismic effects were not inferior to the seismic performance of the original specimen.

(3) Based on the modification and extension of Reihorn evaluation criterion, the earthquake damage evaluation criterion of seismic-damaged CSC columns with strengthening was obtained, which described the specimen from “basically intact” to “complete destroyed”. Then, the seismic damage evolution law of specimen was obtained by quantitative analysis of the test results.

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