# Research on Plastic Design Method of Reinforced Concrete Flexural Component

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*Abstract—The dynamic mechanical properties of reinforced concrete column members under different loading paths in the paper are studied. The influence of loading rate and loading path on the mechanical behavior of reinforced concrete columns is considered. The numerical simulations are performed on the two test-pieces based on the centralized plastic hinge fiber model in OpenSees software.*

*Keywords-Reinforced Concrete; Flexural Member; Plastic Design*

## I.    INTRODUCTION

Reinforced concrete column members are the key components that affect the overall seismic performance of the structure. The force characteristics have great influence on the seismic performance of the structure. The current seismic design specification is based on the quasi-static test results, and does not consider the effect of loading rate on the mechanical properties of materials and components. Since the main deformations in the test process are concentrated in the plastic hinge area, the numerical simulation of the test process is carried out by using the concentrated plastic hinge fiber unit model based on the flexibility method in OpenSees[1-2].

## II.    MATERIAL CONSTITUTIVE MODEL

The plastic hinge unit can simulate the main typical nonlinear behavior of concrete members, which include bond slip effect, shear effect, material nonlinearity. The model can fully reflect the coupling between the two horizontal loading directions and the axial deformation, and the calculation method of the plastic hinge length.

$$\lambda_i = \max \begin{cases} \lambda \kappa + 0.022 \mathrm{f_y d_{bl}} \\ 0.044 \mathrm{f_y d_{bl}} \end{cases} ; k = 0.2 \left( \frac{\mathrm{f_u}}{\mathrm{f_y}} - 1 \right) \le 0.08 \ (1)$$

In equation (1), $\lambda$ is the length of the member; $d_{bl}$ is the diameter of the longitudinal reinforcement; $f_y$ and $f_u$ are the yield strength and ultimate strength of the longitudinal reinforcement under static load, respectively.

The constitutive model of steel bars under cyclic loading has an important influence on the simulation of seismic performance of reinforced concrete columns. In the paper, the Mohle-Kunnath constitutive model is used for the steel bar. The model is composed of the upper elastic rod unit and the plastic hinge unit at the beam end. The enhanced model can be improved to reflect the Bauschinger effect of the steel material and the stiffness and strength degradation effects during low cycle fatigue, and can effectively predict the buckling and fracture of the steel[3-4]. The stress-strain relationship is shown in Fig. 1.
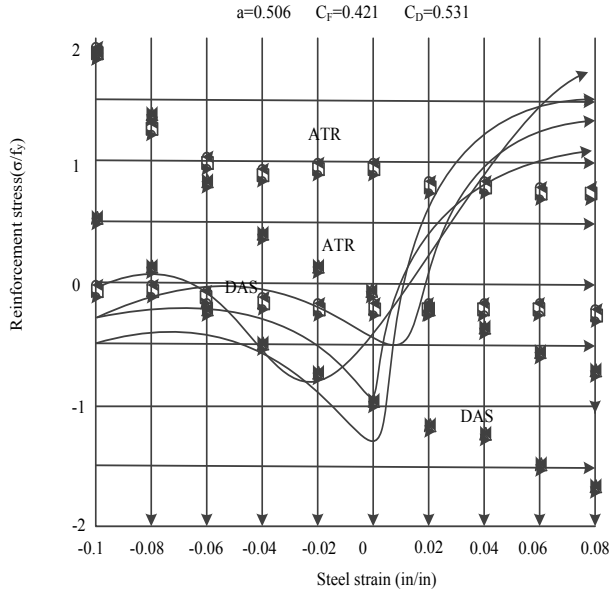
a=0.506    $C_F$=0.421    $C_D$=0.531



Figure 1.   Stress-strain relationship of steel bars

Figure 1 shows the values of the damage accumulation coefficient α, fatigue ductility coefficient $C_f$ and fatigue strength degradation coefficient $C_d$. The strength of steel bars under rapid loading is significantly different from that of slow loading. The rate-dependent effect of steel bars in the paper is considered by introducing the dynamic constitutive model of yield strength and ultimate strength of steel bars. The calculation expression is[5]:

$$\frac{f_{dy}}{f_y}=1+c_y \lg \frac{\dot{\mu}}{\dot{\mu}_0} \tag{:2}$$

$$\frac{f_{du}}{f_u}=1+c_u \lg \frac{\dot{\mu}}{\dot{\mu}_0} \tag{3}$$

$$c_f = 0.1709 - 3.289\times10^{-4} f_y \tag{4}$$

$$c_u = 0.02738 - 2.982\times10^{-5} f_y \tag{5}$$

In equation (2-5), $f_{dy}$ and $f_{du}$ are the dynamic yield strength and ultimate strength of the steel bar after

considering the strain rate of the material, respectively; $f_y$ and $f_u$ are respectively the yield strength and ultimate strength MPa of the steel bar under static load, respectively;

$\dot{\mu}$ is the measured material strain rate, that is, the strain rate at which the longitudinal reinforcement in the plastic hinge region at the bottom of each member yields for the first time;

$\dot{\mu}_0$ is the quasi-static strain rate of the steel bar, and its value is taken as $2.5\times10^{-4}$/s.

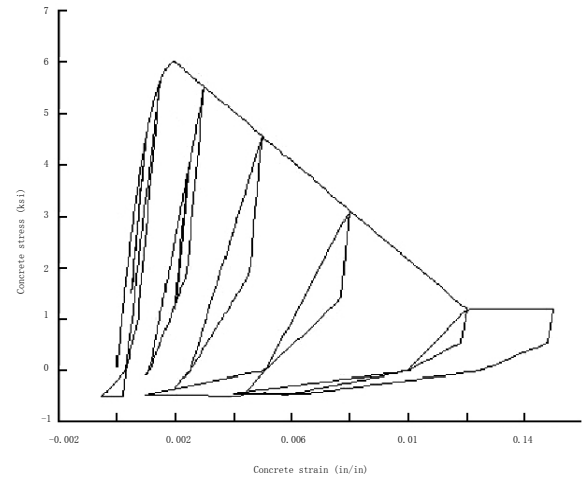The concrete model uses the modified Kent-Park model from Scott et al., as shown in Figure 2.



Figure 2.   Stress-strain relationship of Concrete model

The stress-strain relationship is shown in equation (6).

$$\sigma_c = \begin{cases} kf_c'\left[\frac{2\mu_c}{\mu_0}-\left(\frac{\mu_c}{\mu_0}\right)^2\right], & \mu_c < \mu_0 \\ kf_c'\left[1-z_m(\mu_c-\mu_0)\right], & \mu_0 \le \mu_c < \mu_{20} \\ 0.2kf', & \mu_c > \mu_0 \end{cases} \tag{6}$$

$$\mu_0 = 0.002K, \quad K = 1+\frac{\rho_s f_{yh}}{f_c'} \tag{7}$$

The model can reflect the restraint effect of the stirrup by adjusting the peak stress, the peak strain value and the slope of the softening section, and can effectively predict the residual strength of the concrete. The skeleton curve consists

of three stages, which are the ascending section, the descending section and the stationary segment. In the mathematical expression: K is the concrete strength improvement coefficient caused by the influence of the stirrup constraint, 0.002K is the concrete strain value corresponding to the peak stress; $Z_m$ is the slope of the strain softening section; $f_c'$ is the concrete compressive strength MPa when no hoop restraint is affected; $f_{yh}$ is the yield strength MPa of the stirrup; $\rho_s$ is the volume hoop ratio; $s_h$ is the hoop spacing; h' is the width of the concrete in the core zone from the outer edge of the stirrup provided for the cross section of the column. The dynamic tensile and compressive strength of concrete is different from the tensile and compressive strength during static loading. In the paper, the rate-dependent constitutive model proposed by the European Concrete Commission is used to consider the influence of material strain rate on the tensile and compressive strength of concrete. The calculation equation of dynamic tensile and compressive strength is as follows:

$$\frac{f_{dt}}{f_t} = \left(\frac{\dot{\mu}}{\dot{\mu}_0}\right)^{1.016a}, \frac{f_{dc}}{f_c} = \left(\frac{\dot{\mu}}{\dot{\mu}_0}\right)^{1.016b} \qquad (8)$$

In equation (8), $f_t$ and $f_{dt}$ are the static tensile strength and dynamic tensile strength of concrete, respectively. The tensile strength of concrete in the paper is taken as 0.1 times of compressive strength. $\dot{\mu}$ is the measured material strain rate, and the strain rate of the steel bar in the plastic hinge region of each component is taken as the first yield. $\dot{\mu}_0$ is the quasi-static strain rate of concrete, which value is 1×10-5/s, $f_0$ is a constant, which value is 10MPa.

According to the measured strain rate value of the steel material under the fast loading condition, and the strength and rate related constitutive structures of the concrete and steel materials are combined, the main strength index values of the concrete and the steel material during rapid loading can be obtained, as shown in Table 1.

TABLE I.        THE MAIN STRENGTH INDEX OF MATERIAL

| Material index | Test-piece number | | | |
|---|---|---|---|---|
| | RC1 | RC2 | RC3 | RC4 |
| $\dot{\mu}(10^{-2}/s)$ | 4.68 | 4.28 | 5.98 | 5.26 |
| $f_{dc}/MPa$ | 35.6 | 35.4 | 35.9 | 35.6 |
| $f_{dt}/MPa$ | 3.66 | 3.64 | 3.69 | 3.68 |
| $f_{dy}/MPa$ | 388.0 | 387.7 | 390.1 | 389.7 |
| $f_{du}/MPa$ | 529.5 | 528.9 | 529.9 | 529.5 |

The calculation results can be obtained based on numerical simulation. It can be seen from the comparison of the main mechanical indexes of the test results obtained by the simulation results and the load-displacement of the test results. The simulation results under different loading paths are basically consistent with the experimental results. It can also be seen from the limit load point of the load-displacement curve to the curve change between the failure points. In the paper, the falling curve of the simulation results is relatively slow, and the bearing capacity of the test piece decreases slowly. Therefore, the test-pieces corresponding to the simulation results are slightly more ductile than the test results.

In addition, the model does not consider the effect of loading rate on the bond slip of the test piece. According to the test results, the bond slip strength increases as the loading rate increases. Therefore, the calculated bearing capacity curve is slightly lower than the test results.

In summary, the calculation model selected in the paper can effectively simulate the main mechanical characteristics of column members under fast loading conditions.

## III. CONCLUSIONS

According to the research in this paper, the increase of the yield load of the specimen under the fast loading condition is higher than the ultimate load; when loading in both directions, the reinforcing bar gradually softens with the deformation, and the first loading direction is more affected by the loading rate; as the loading rate increases, the ductility of the test-piece decreases and the deformability decreases; It is summarized as follows:

*1)* With the increase of deformation dimension, compared with unidirectional loading, the bidirectional loading is degraded due to the coupling effect, and the test-piece is degraded and the strength degradation speed is accelerated. At the same time, the unloading stiffness and the reloading stiffness are also reduced to different extents, the test-piece breaks ahead and the deformation capacity decreases.

*2)* Among the three bidirectional loading paths, the load capacity of the cross-shaped loading path specimens is the smallest, and the influence of each mechanical performance index is low. The rhombic loading path specimens have the largest reduction in ductility, stiffness and strength degrade most rapidly, the mechanical properties of the test-pieces are most affected by the loading rate.

*3)* The centralized plastic hinge beam unit in OpenSees software, Improved Kent-Park concrete constitutive model by Scott et al. and the Mohle-Kunnath reinforced constitutive model, and the calculation model established by considering the strain rate effect of the material can effectively simulate the main dynamic mechanical properties of reinforced concrete columns at different loading rates.

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