PLASTIC-DAMAGE ANALYSIS OF RCC DAMS STRENGTHENED WITH STEEL FIBER REINFORCED CONCRETE IN MONOLITH FOR SEISMIC RESISTANCE

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ABSTRACT:
In the paper, damage failure in the water-retaining monolith of Jin'an Qiao RCC dam subjected to strong ground motion is simulated by a concrete damaged plasticity model based on damage index variables of tensile stress. The effects of steel fiber reinforced concrete(SFRC) to strengthen the dam are studied by using three different dimensions of SFRC zones and three volume ratios of SFRC. According to the above combination of SFRC's applied zones and volume ratios, the variable rules of equivalent crack width , crack expansion depth, displacement response and starting crack acceleration are analyzed respectively. The comparison of calculation results shows the measure can remarkably reduce the damage zone, significantly control the extension of damage zone and effectively improve the aseismic performance of the dam.

KEYWORDS: Plastic-damage model, Damage index variable of tensile stress, Aseismic measure, Steel fiber reinforced concrete

1. INTRODUCTION

Entering the 21st century, strategetic tasks in China, such as the Western Development Drive and the West-East Power Transmission Project, have improved unprecedented development of hydraulic power exploitation and hydraulic engineering construction[1-2]. Some high dams over 200m, even 300m in height, have been built or will be built immediately in Southwest China[3].As is well known, nearly 70% of national total hydropower potential is concentrated in the Southwest of China, and the region is also notable for its high seismic intensity and frequent occurrence. According to the statistics[4], about 40% of dams, with a reservoir more than 100 million cubic metres in volume, are located in the area of seismic intensity larger than Ⅶ, and 13% in the area of seismic intensity larger than Ⅷ. Therefore, seismic safety of large dams is one of the key problems that need to be solved in the design of dams.

Effective engineering measures can play an important role in bettering dam safety and enhancing resistance to accidental loads. At present, these measures, including anti-seismic steel bars and anchor cables laid down in easy cracking regions of dams[5-9], steel fibre reinforced concrete(SFRC) filled into the high stress regions of dams[10-13], engineered cementitious composites(ECC) painted on the surface of dams to prevent dam cracking[14-15], etc, have become a new research hotspot in the seismic safety of dams.

Based on the engineering background of Jin'an Qiao rolled concrete gravity dam under construction, a plastic-damage finite element analysis on the SFRC-strengthened aseismic measure for the water-retaining monolith of Jin'an Qiao RCC dam is carried out in the paper. In this numerical analysis, the effect of the SFRC's earthquake-resistant measure on starting crack state and crack propagation of the water-retaining monolith is numerically simulated by a concrete damaged plasticity model based on damage index variables of tensile stress including the combination of three volume ratios of SFRC and three kinds of dimensions of the strengthened zones. In sum, this study aims to improve understandings in the aseismic performance of SFRC, and discuss the feasibility of this measure in practical engineering application.

2.DAMAGED PLASTICITY CONSTITUTIVE MODEL OF CONCRETE

The concrete damaged plasticity model is adopted for the numerical analysis in this paper. The model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the yield surface is controlled by two hardening variables, $\tilde{\varepsilon}_t^{pl}$ and $\tilde{\varepsilon}_c^{pl}$, linked to failure mechanisms under tension and compression loading, respectively. $\tilde{\varepsilon}_t^{pl}$ and $\tilde{\varepsilon}_c^{pl}$ are referred as tensile and compressive equivalent plastic strains, respectively.

The tensile cracking performance of concrete is highlighted in this study. The constitutive models of both plain concrete(i.e. dam body concrete) and SFRC(i.e. the reinforcement material) to uniaxial loading in tension are selected as shown in Fig.1, in which three SFRC volume ratios including 1%, 1.5% and 2% are considered for the SFRC model. Meanwhile, the uniaxial tensile response of concrete is characterized by damaged plasticity, as shown in Fig. 2.

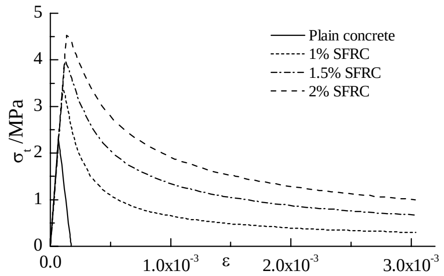


Fig.1 Uniaxial tensile stress-strain curves of plain concrete and SFRC

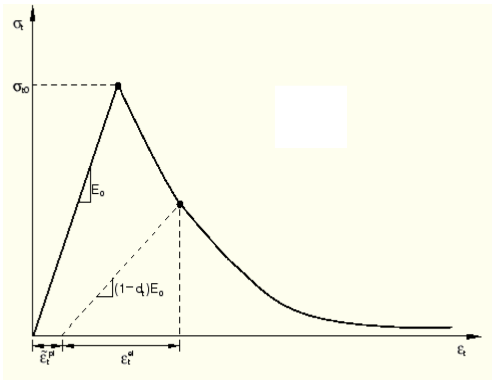


Fig.2 Damage plasticity model of plain concrete and SFRC

Fig.2 shows that under uniaxial tension, the stress-strain response follows a linear elastic relationship until the value of the failure stress, σ_{t0}, is reached, and the failure stress corresponds to the onset of micro-cracking in the concrete material; And beyond the failure stress, the formation of micro-cracks is represented macroscopically with a softening stress-strain response, which induces strain localization in the concrete structure.The tensile damage factor d_t is given to depict the reduction of the elastic modulus of concrete in the concrete damaged plasticity model,

$$d_t = 1 - \frac{E}{E_0} \quad (0 \le d_t \le 1) \tag{2.1}$$

Where E_0 is the initial(undamaged) modulus of the material; E is the damaged modulus of the material.

In order to avoid unreasonable mesh sensitivity in the finite element analysis, the concept of fracture energy, G_f, defined as the energy required to open a unit area of crack, is introduced and accordingly, the concrete's postfailure cracking behavior is characterized by a stress-displacement response rather than a stress-strain response, as shown in Fig.3. Similarly, tensile damage, d_t, is specified as a function of cracking displacement, as shown in Fig. 4. In these two figures, cracking displacement, u_t^{ck}, is defined as the product of unit cracking strain and unit length[16].The stiffness degradation damage caused by compressive failure of the concrete is assumed to be zero.

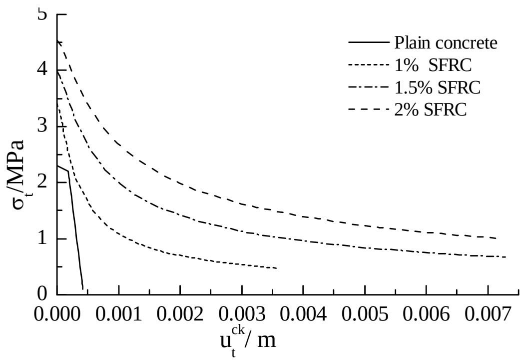


Fig. 3 The stress-displacement curve

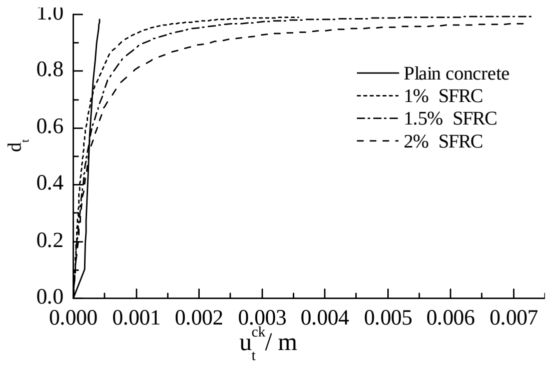


Fig.4 The damage-displacement curve

3.ENGINEERING APPLICATIONS

The Jin'an Qiao rolled concrete gravity dam is selected for the study of the effect of steelfiber-strengthened aseismic measure on the dam security. The 4×600 MW Jin'an Qiao hydroelectric station with a high dam of 160 m is the first station developed at the middle reaches of the Jin sha river, which is the fifth-class electric station of the whole programming "one reservoir eight classes" project at the Li river region of Yunnan Province. In accordance with site appraisal performed by the geologic institute of China earthquake administration, the basic earthquake intensity reaches to 8 degrees and the protected intensity is up to 9 degrees; The earthquake motion acceleration of 2.0% transcendental probability in 100-year base period reaches to 0.3995g. It is the first time to build a rolled concrete gravity dam in such rough site condition for all the Chinese hydraulic engineerings.

Aseismic design of rolled concrete gravity dams is the most decisive technical matter in the design of Jin'an Qiao electric station. Therefore, it is necessary to specially assess aseismic security of the dam and to further study aseismic measures for the dam in order to ensure reliability of security assessment and economical efficiency of these measures.

In the earlier stage, sectional and integral dynamic shaking table model tests were performed[15] and the result that non-penetrating cracks happened under the design earthquake load was got. Based on the model tests, the numerical analysis of SFRC measures for the dam is performed.

The material properties for the concrete are: unit weight $=2400\,kg/m^3$, modulus of elasticity$=3.315\times10^4\,MPa$, Poisson's ratio$=0.167$. Since the value of fracture energy, G_f, has relationship with many factors, the experimental results of G_f differs dramatically due to different test modes and component sizes. For the small-size concrete components in the three point bending tests[17,18], the value of G_f is less than $200\,N/m$.But the results from the small-size concrete tests are not suitable for mass concrete like dam concrete. Xu et al.[19] conducted tensile tests for determining fracture energy of concrete on huge compact specimens having different dimensions of 3.6×3.0, 3.0×2.5, 2.4×2.0, and 1.8×1.5 m, with the same thickness of 0.2m.And they got the average value of $498.4N/m$. So the G_f value of $500N/m$ is adopted for the dam body concrete in this paper. Meanwhile, according to the experimental researches by Shi et al.[20] and Li et al.[21], the G_f value of SFRC with three volume ratios of 1%, 1.5% and 2% is 3 times, 3.5 times and 4 times higher than that of the dam body concrete, respectively.

3.1. Considerations of crack

In this paper, the equivalent crack open-displacement, namely the equivalent crack width, is considered as a main index of earthquake-induced dam damage[22].For the scalar damage constitutive model of concrete, according to the continuum damage mechanics, damage factor, d_t, stress tensor, σ, and total strain tensor, ε

must meet the following formulation,

$$\boldsymbol{\sigma} = (1-d_t)\boldsymbol{D_e} : \boldsymbol{\varepsilon} \tag{3.1}$$

where $\boldsymbol{D_e}$ is the linear elastic stiffness tensor. And the non-elastic strain tensor, $\boldsymbol{\varepsilon}_{in}$, can be written as,

$$\boldsymbol{\varepsilon}_{in} = \boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_e = \boldsymbol{\varepsilon} - \boldsymbol{D}_e^{-1} : \boldsymbol{\sigma} = d_t\, \boldsymbol{\varepsilon} \tag{3.2}$$

Assuming that the direction of the first principal strain, $\varepsilon_{in}^{\max}$, is the normal direction of crack, and letting the cracking strain $\varepsilon_t = \varepsilon_{in}^{\max}$. So the equivalent crack open-displacement, w, must meet,

$$w = h\,\varepsilon_{in}^{\max} = h\,d_t\,\varepsilon^{\max} \tag{3.3}$$

in which $\varepsilon^{\max}$ is the first principal strain component of the total strain tensor, $\boldsymbol{\varepsilon}$; h is the unit width of the fracture zone.

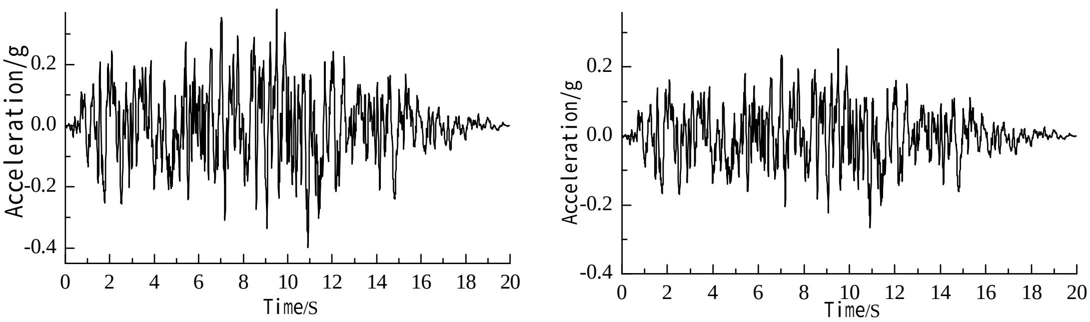
The cracks where the equivalent opening displacement is more than 0.1mm are regarded as macroscopical cracks and are mainly studied in the numeric analysis. Meanwhile, cracks in the dam-heel zone are not analyzed because of its complex stress state.

3.2 Considerations of loading

In the analysis, loads are considered as follows:
(1) dead load of dam;
(2) hydrostatic pressure of 137 m water head at the normal pool level;
(3) the added mass per unit area of the upstream wall is given in the following form,

$$\frac{7}{8}\rho_w\sqrt{h_w(h_w - y)}\ ,(\ y \le h_w\ ) \tag{3.4}$$

where $\rho_w = 1000\,kg/m^3$ is the density of water; y is the depth of water; h_w is the gross water head.
(4) Earthquake excitation. The bidirectional earthquake waves generated by the standard code spectrum are selected as shown in Fig.5 . The horizontal components are adjusted in amplitude to 0.3995g, namely the peak design acceleration in the dam area of Jin'an Qiao hydroelectric station. The acceleration summit in the vertical direction is adjusted to two thirds of that in the horizontal direction.



(a) Horizontal acceleration time history　　(b) Vertical acceleration time history

Fig.5 Acceleration time history of code-spectrum generated wave

3.3 FE model and SFRC strengthened schemes

A two-dimensional finite element model of the water-retaining monolith in rigid foundation is set up, which is shown in Fig.6. A plastic damage analysis for the water-retaining monolith subjected to earthquakes is performed to determine the SFRC-strengthened positions. And the damage envelope lines that the damage values are greater than 0.05, correspondingly the crack open-displacements are more than 0.1mm, are drawn in

Fig.7.

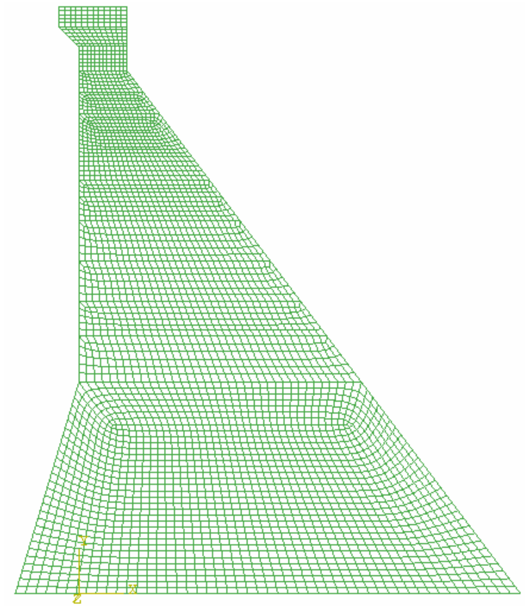


Fig.6 The FE model

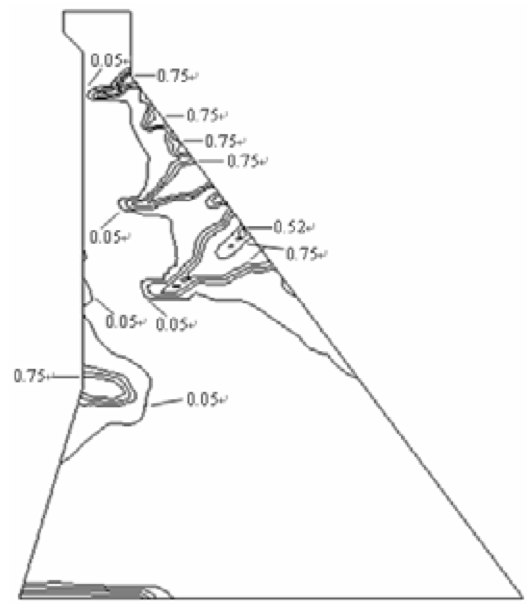
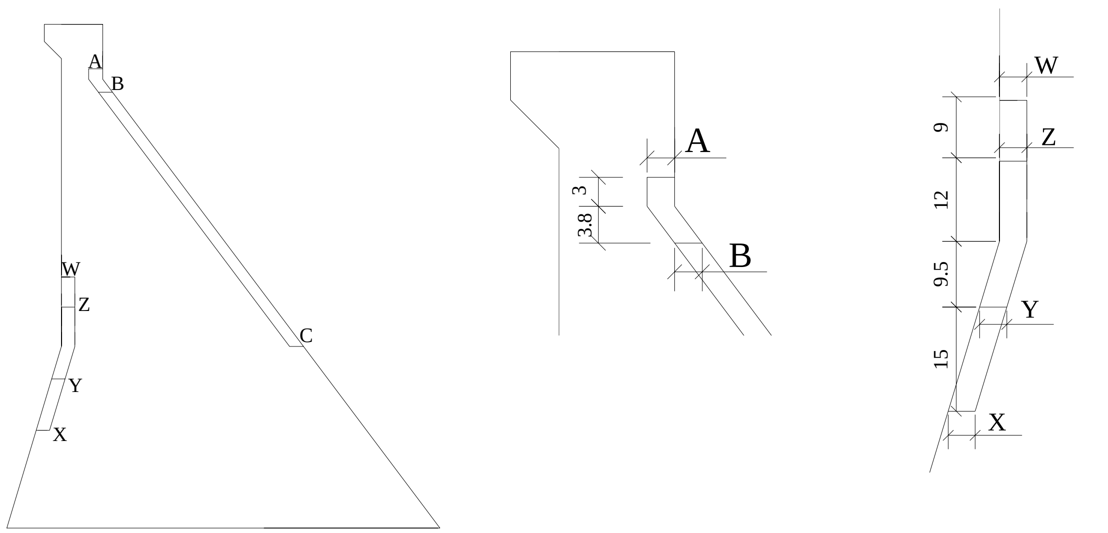


Fig.7 Dam body concrete damage distribution

According to the result of the plastic damage analysis, three SFRC-strengthened schemes are presented to study the SFRC effect on dam . three dimensions of the SFRC regions which represent the SFRC amount used and three volume ratios of SFRC are considered in these schemes. The specific reinforcement positions and dimensions are shown in Fig.8 and Tab.1.



(a)The general arrangement diagram (b)Local diagram Ⅰ (c) Local diagram Ⅱ

Fig.8 The SFRC-strengthened arrangement plan

Table 1. The dimensional parameters of the SFRC-strengthened regions

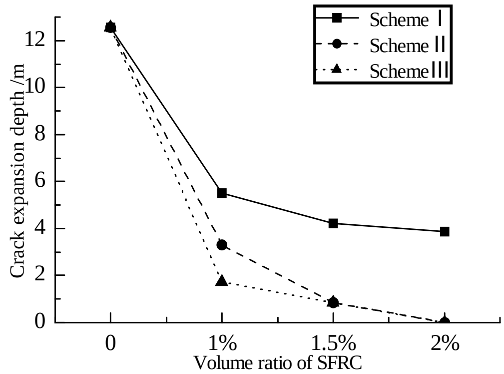
Scheme	A(m)	B(m)	C(m)	X(m)	Y(m)	Z(m)	W(m)
Ⅰ	1	1	1.5	2	2	2	1
Ⅱ	2	2.5	2.5	2	4	4	1
Ⅲ	3	4	3.5	4	4	4	2

3.4 Analysis of numerical results

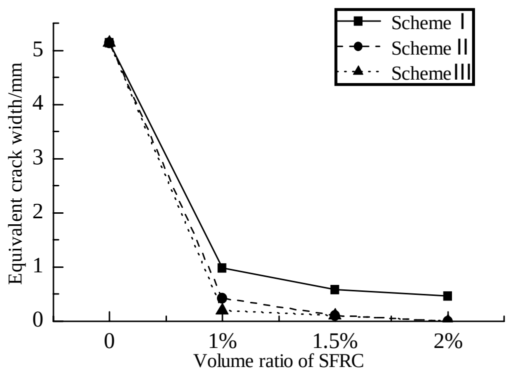
Based on the built FE models, we systematically study the comprehensive effects of the SFRC reinforcement measures on aseismic safety of dam. From different analytical angles, the main features of the effects, including equivalent crack width, crack expansion depth, dam crest displacement, and starting crack acceleration of dam are next discussed in turn.

(1) Equivalent crack width and crack expansion depth

Equivalent crack width which is defined in section 3.1 and crack expansion depth are used to evaluate the effect of the SFRC measures with three volume ratios on the seismic safety of the Jin'an Qiao dam. Fig.9(a) and Fig.9(b) show that the depth and width of crack drop dramatically when the three schemes of the SFRC measures are used. Compared with the non-measure scheme, the equivalent crack width of the three SFRC schemes decreases in the range of 80%-100% while crack expansion depth decreases in the range of 56%-100%. Meanwhile, the amount of SFRC in Scheme Ⅲ is 1.5 times than that in SchemeⅡ, but the decrease rates of crack width and crack depth in the both Schemes are nearly the same. This indicates that there exists a economical equilibrium value in the use amount of SFRC.



(a)Crack expansion depth



(b)Equivalent crack width

Fig.9 The depth and width of crack with and without SFRC measures

(2) Dam crest displacement

Residual plastic displacement of the dam crest at the final motion time of earthquake can be used to value the ductile performance of dam subjected to earthquake. Fig.10 shows that the vertical and horizontal residual plastic displacement in Scheme Ⅲ with 2% volume ratio of SFRC decreases a lot , compared with that of the non-SFRC measures. Meanwhile, the peak displacements of the three Schemes in the both directions also drop as shown in Fig.11.This indicates that the use of SFRC in the high-stress zones can increase concrete ductility, dissipate a great deal of earthquake-input energy , and enhance the aseismic capability of dam.

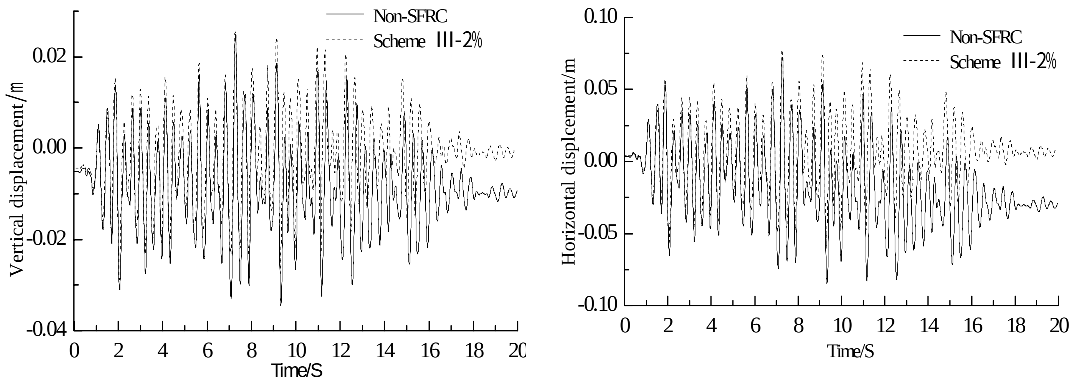


Fig.10 Displacement time history of dam crest

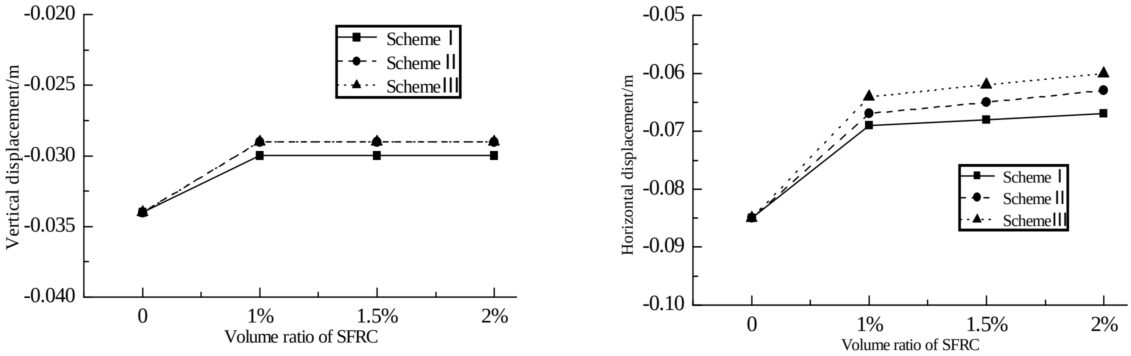


Fig.11 Vertical and horizontal peak displacement comparison

(3) Starting crack acceleration of dam

With the use of SFRC, starting crack acceleration of dam can increase from 0.22g to 0.45g, a rise of 104%, as indicated in Tab.2. Fig.12 also shows that with the increase of SFRC amount and volume ratio of SFRC, Starting crack acceleration grows gradually. But the fact that curves of Scheme Ⅱ and Scheme Ⅲ in Fig.12 nearly coincide, indicates the existence of equilibrium of the SFRC amount, just as discussed in Section 3.4(1).

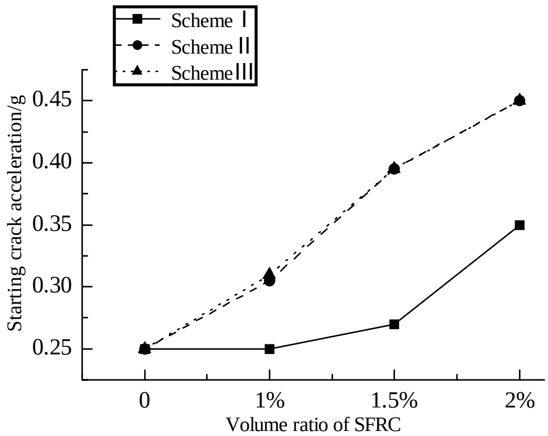


Fig.12 Starting crack acceleration in three schemes with different volume ratios of SFRC

Table 2. Starting crack acceleration with and without SFRC measures

Scheme	Non-SFRC	Ⅰ-1%	Ⅰ-1.5%	Ⅰ-2%	Ⅱ-1%	Ⅱ-1.5%	Ⅱ-2%	Ⅲ-1%	Ⅲ-1.5%	Ⅲ-2%
Starting crack accelration (g)	0.22	0.27	0.35	0.31	0.305	0.40	0.45	0.31	0.395	0.45

4. CONCLUSIONS

This paper has developed a plastic damage analysis of RCC dam strengthened with SFRC exploring the influence of SFRC measures on the seismic safety of the dam. Conclusions have been drawn as follows:

(1) The plastic damage model adopted in this paper can factually simulate the SFRC effect on dam, which provides a FE method of numerical analysis for studies on the aseismic techniques of RCC dam.

(2) The use of SFRC at the high-stress regions of dam can increase concrete ductility, dissipate a great deal of earthquake-input energy , and enhance starting crack acceleration of dam.

(3) The use of SFRC can defer crack appearance, control crack propagation, delay the crack-penetration time and strengthen the seismic-resistance capacity of dam under rarely-occurred earthquakes.

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