SHRINKAGE PREDICTED MODEL OF CONCRETE FILLED STEEL TUBE AND SHRINKAGE STRESS OF CONCRETE FILLED STEEL TUBULAR ARCH

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SUMMARY

Taking strength of concrete, content of fly ash, and steel tube diameter as well as steel ratio as the main parameters, shrinkage tests of 11 CFST and 2 air-tight plain concrete specimens are carried out in this paper. Predictions of the shrinkage deformation of the specimens by the common shrinkage models indicate that the ACI 209R-92 model could give high precision prediction and can be used to predict the shrinkage of CFST members when the content of fly ash of the concrete infill is less than 20%, while when the content of fly ash is no less than 20% the model should be modified. The prediction results by CEB-FIP MC90 model and CEB-FIP MC78 model are significantly smaller than the tested ones. Analyses of shrinkage stresses of CFST arch bridges show that the shrinkage self-stress is large and should be taken into account in design calculation, whereas the secondary shrinkage stress is small and could be ignored in stress estimation during preliminary design. The equivalent cooling temperature method is common used for calculation of shrinkage effect of concrete arch. However, it is not suggested to be used in design calculation of shrinkage effect of a CFST arch due to its shrinkage deformation varies in a large rang and it is difficult to recommend an equivalent cooling temperature value, moreover, this method cannot calculate the shrinkage self-stress which is the main shrinkage stress.

Keywords: *Concrete filled steel tube, arch bridge, shrinkage, experiments, predicted model, stress.*

1. INTRODUCTION

CFST arch bridges are widely used in highway and urban bridges in China, as well as the increasing application in high-speed railway bridge in recent years. As a composite structure, the shrinkage stress of CFST structures must be taken into account during design. The shrinkage stress includes the self-stress and secondary stress. Due to the restraint of steel tube, the shrinkage of CFST member is less than sealed concrete. According to the compatibility condition of deformation, it will cause pressure stress for steel tube and tensile stress for concrete infill due to shrinkage, called shrinkage-induced self-stress. For the statically indeterminate CFST arch bridge, the secondary force or secondary stress will be caused by shrinkage, called shrinkage-induced secondary stress. How to calculate the shrinkage strain is the key problem to calculate the shrinkage stress for CFST arch bridge. Shrinkage of CFST member is different from normal concrete because of the sealed concrete and restraint of steel tube to concrete infill.

Some shrinkage test for CFST members have been carried out in the world [1-8]. All the shrinkage tests of CFST member are taken as the contrast members of creep to deduct the influence of shrinkage, therefore, the results are large discreteness and lacking regularity. Special shrinkage experiments for the influence of many factors are not yet reported. Considering the special working performance of CFST arch bridge, strength of concrete, content of fly ash, and steel tube diameter as well as steel ratio are taken as the main parameters, shrinkage tests are carried out in this paper. Hence, we can know the shrinkage character of CFST members, which give foundation for selecting a reasonable shrinkage predicted model.

For the calculation of shrinkage deformation of concrete, the code of TB10002.1-2005 [9] and JTG D62-2004 [10] recommend the CEB-FIP MC78 model and CEB-FIP MC90 model, respectively. No shrinkage predicted models are recommended both in the code of DBJ/T 13-136-2011 [11] and CQJTG/T D66-2011 [12] for the calculation of CFST arch bridge, but the ACI 209R-92 model and CEB-FIP MC90 model are recommended to calculate the creep of CFST arch bridges, respectively. The Chinese design code "Technical Code for CFT Arch Bridges (GB 50923-2013) [13]" also recommended the CEB-FIP MC90 model to analyze the shrinkage of CFST arch bridge. Therefore, CEB-FIP MC78 model, CEB-FIP MC90 model and ACI 209R-92 model are the three shrinkage predicted models widely known in the world. But the evaluations for the three models predicting shrinkage of CFST members are not analyzed at currently. Based on the test research, this paper evaluates the three shrinkage models and recommends the best model to be used.

For the calculation of shrinkage secondary force of concrete and reinforced statically indeterminate structure, the code of TB10002.1-2005 [9] recommends the equivalent cooling temperature method. The other design code "General specifications for design of highway bridges and culverts (JTJ 021-89)" [10] also adopts the similar method to calculate the shrinkage effects. For a long time, many Chinese designers also adopted the equivalent cooling temperature method to compute the shrinkage secondary force for CFST arch bridges. Lai and Chen [14] show that the results from equivalent cooling temperature of 15℃~20℃ are larger than from shrinkage predicted models. Due to lacking the shrinkage test results of CFST members, deeper analysis is not carried out. Therefore, this paper will deeply discuss the application of equivalent cooling temperature method by calculating the shrinkage strain for common use concrete. Case study on the shrinkage stress of a CFST arch bridge is also carried out in this paper.

2. SHRINKAGE TEST FOR CFST MEMBER

2.1. Specimen design

The common range of diameter of steel tube is from 600 mm to 1300 mm for CFST arch bridge, and the most commonly used is nearby 1000 mm. The range of steel tube diameter is selected from 165 mm to 1000 mm by considering the limited experiment condition. All the thickness of steel tube is 2 mm except the diameter of 600 mm and 1000 mm is 8 mm. The length of specimens is 600 mm. The steel ratio varies from 0.030 to 0.056.

Seven groups of mix proportion are designed to consider the two parameters of grade of concrete and fly ash content. The group of M1 is grade of C40, M2 is C60, M3 to M7 is

C50 with adding fly ash by content of 10% to 40%. According to the engineering experience and standard requirement, the slump of concrete infill is required a range of 200mm to 260 mm when pumping; the water-binder ratio is not larger than 0.35. Therefore, slump of concrete infill is 230 mm in this test; water-binder ratio is range of 0.29 to 0.41 (the group of M1 is slightly larger than 0.35 for meeting the required strength and slump). Materials used in the experiments are: ordinary Portland cement branded of Fujian Lianshi P.O 425; crushed Granit with largest diameter of 30mm; sand from Minjiang River; fly ash of class II; polycarboxylate super-plasticizer of CX-8 with 25% of water-reducing ratio produced by a company in Fuzhou city.

According to the three parameters of steel tube diameter (or steel ratio), concrete strength and fly ash content, there are four groups with 11 CFST specimens and 2 air-tight plain concrete specimens for shrinkage test. All the specimens are numbered according to group, diameter of steel tube, grade of concrete and content of fly ash; S means the CFST specimens, P means air-tight plain concrete specimens; S1 means parameter of diameter of steel tube, S2 is strength of concrete, S3 is content of fly ash; such as S1-D2-C50-10 means the first group CFST specimens with diameter of 219 mm, grade of concrete C50 and content of fly ash 10%. The main parameters of all specimens are showed in Tab. 1.

Table 1. *List of CFST shrinkage specimens.*

No.	Group	Specimens	D×t [mm]	Steel Ratio	Grade of Concrete	Fly Ash Content	Remark
1	I	S1-D1-C50-10	165×2	0.050	C50	10%	M3
2		S1-D2-C50-10	219×2	0.038	C50	10%	M3
3		S1-D3-C50-10	273×2	0.030	C50	10%	M3
4		S1-D4-C50-10	600×8	0.056	C50	10%	M3
5		S1-D5-C50-10	1000×8	0.033	C50	10%	M3
6	II	S2-D1-C40-10	165×2	0.050	C40	10%	M1
7		S2-D1-C60-10	165×2	0.050	C60	10%	M2
8	III	S3-D1-C50-0	165×2	0.050	C50	0%	M4
9		S3-D1-C50-20	165×2	0.050	C50	20%	M5
10		S3-D1-C50-30	165×2	0.050	C50	30%	M6
11		S3-D1-C50-40	165×2	0.050	C50	40%	M7
12	IV	P01-D1-C50-10	165×2	0.050	C50	10%	M3
13		P02-D1-C50-10	165×2	0.050	C50	10%	M3

2.1 Fabrication of specimens and testing set-up

All the CFST specimens are fabricated as required length and diameter of steel tube. The steel deck plates at both ends are completed at the same time. One of the steel plates was welded at the end of steel tube before casting concrete. The other one was welded after casting the concrete into steel tube. The air-tight plain concrete members are used to measure the shrinkage under sealed condition; a plastic membrane is paved on the template before casting concrete and after casting paraffin is wiped outside the concrete to keep the concrete sealed.

In order to remove the influence of temperature, all the specimens are put in a sealed laboratory and its temperature is controlled at 24±1°C. The humidity of the laboratory is not controlled because of all the specimens are sealed.

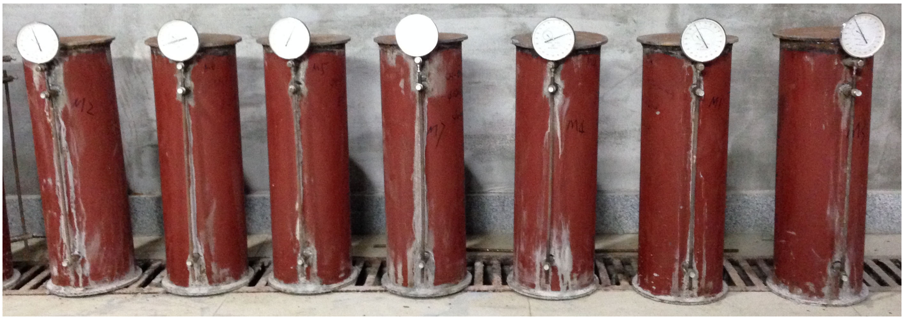
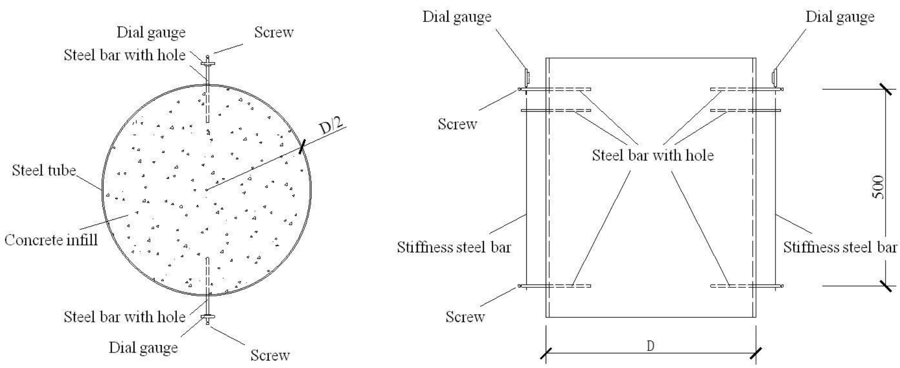


Fig. 1. *Test pictures of some specimens.*



(a) layout *(b) elevation*

Fig. 2. *Measure set-up (unit: mm).*

Fig. 2 shows the measure set-up of shrinkage deformation. There are 6 holes on the symmetric face (3 holes at each face) used to fix the steel bar and the dial gage, as shown in Fig. 2b.

2.2. Overall results

Fig. 3 shows the time-history of tested shrinkage strain for all CFST specimens. The results show that all the specimens have the same law of development but different value. A total of 180 days the shrinkage strain was measured; it developed faster before 60 days; it was over 75% of the total shrinkage strain at 60 days; after that the speed is slower; it was over 90% when 100 days; the curve of shrinkage strain is trend to be horizontal and be stability.

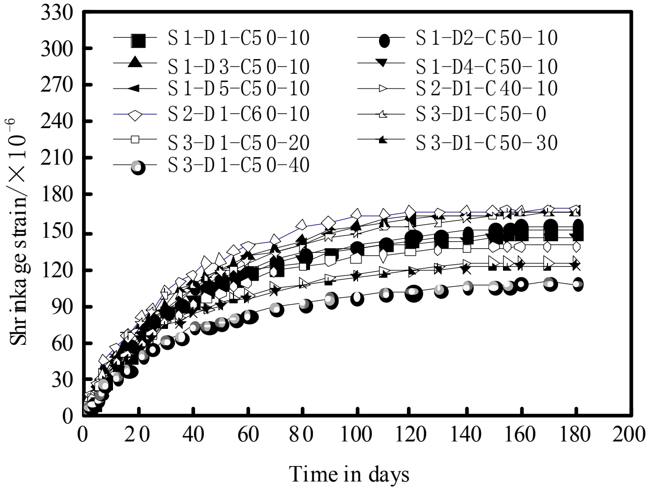


Fig. 3. *Tested results of all CFST specimens strain between CFST.*

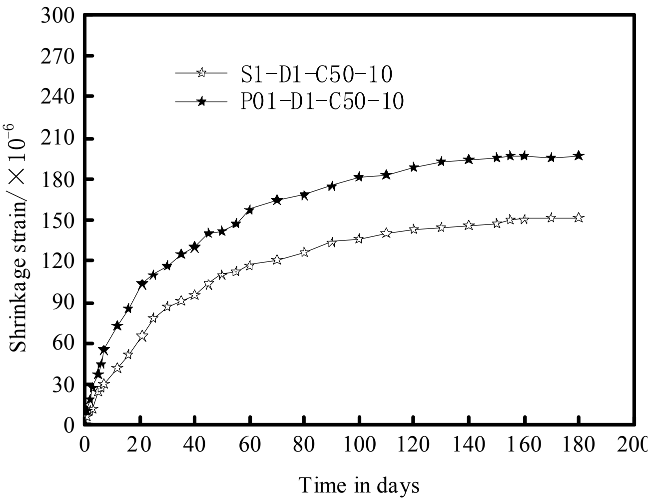


Fig. 4. *Comparison of shrinkage member and air-tight plain concrete.*

The shrinkage developmental law of CFST member is similar to the air-tight plain concrete member, but the former is smaller 22.8% than the latter at 180 days. The shrinkage strain of CFST member at 60 days and 100 days is 76.9% and 90.1% of the total, respectively; the air-tight plain concrete member is 80.2% and 91.9%. Therefore, the early shrinkage developmental rate of CFST member is slower than the air-tight plain one.

3. SHRINKAGE PREDICTED MODELS FOR CFST MEMBER

3.1. Shrinkage predicted models for sealed member

As we know, the shrinkage of CFST member is closely related to concrete infill. In order to get a suitable shrinkage predicted model, three common used shrinkage models, i.e. CEB-FIP MC78 model [15], CEB-FIP MC90 model [10] and ACI 209R-92 model [16], are selected to compare the test results of sealed concrete.

The fourth group is the sealed member in this paper. All the parameters such as environmental relative humidity, strength of concrete, content of cement, effective thickness of members and so on, are considered in the three models. The results at 180 days show that the shrinkage strain predicted by CEB-FIP MC78 model, CEB-FIP MC90 model and ACI 209R-92 model are 198$\mu\varepsilon$, 103$\mu\varepsilon$ and 33$\mu\varepsilon$, respectively; the ratio of predicted results to test is 1.01 for ACI 209R-92 model, 0.52 for CEB-FIP MC90 model and 0.17 for CEB-FIP MC78 model. The ACI 209R-92 model is the best one for predicting the shrinkage of sealed member, as shown in Fig. 5.

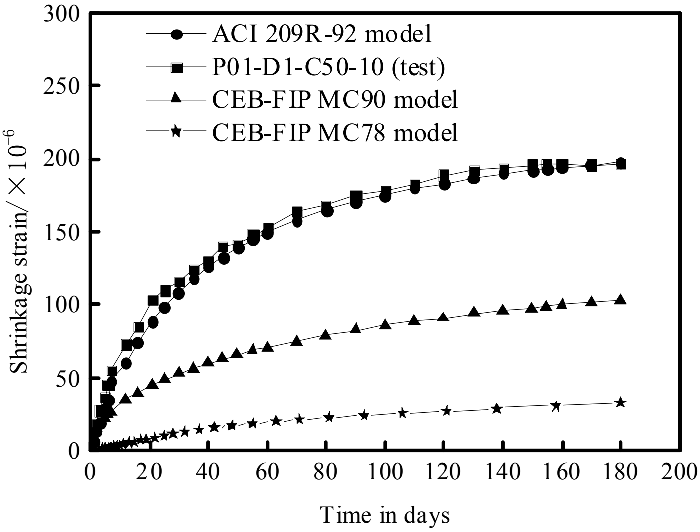


Fig. 5. Comparison between test and predicted results.

3.2. Shrinkage predicted models for CFST member

The three shrinkage predicted models are used to calculate the shrinkage strain for 11 CFST specimens. In this paper, the relative humidity is assumed to be 90%. This is a reasonable assumption because the concrete infill is sealed by the steel tube. Other required parameters were calculated accordingly for the three shrinkage prediction models. For ACI 209R-92 model, the factor considered member size is 1.0 because the shrinkage of sealed concrete is nothing to do with member size. But it is taken into account for CEB-FIP MC90 model and CEB-FIP MC78 model practically. The results predicted by the three models compared with test are showed in Tab. 2.

Tab. 2 shows the same results as sealed concrete, i.e. the ACI 209R-92 model predicted best with the measured value for CFST members, the CEB-FIP MC90 model is the second one and the CEB-FIP MC78 model is the worst one.

As we know, both the CEB-FIP MC78 model and CEB-FIP MC90 model are mainly used to calculate the drying shrinkage. The parameters such as effective thickness, ambient relative humidity, concrete strength and the influence of time are proposed based on considering the drying shrinkage. Both the two models are without considering the influence of adding fly ash.

The influence of concrete strength on shrinkage is not reflected in CEB-FIP MC78 model. While it is taken into account in the CEB-FIP MC90 model, which is based on drying shrinkage but not chemistry shrinkage. The drying shrinkage is decreasing with the increasing of concrete strength, which is contrary to the shrinkage law of sealed concrete. Therefore, both the two models can not reflect the shrinkage development of sealed concrete.

The influence factors considered in ACI 209R-92 model are independent. It is easy to set relevant parameter to calculate shrinkage according to the environmental condition. The coefficient of member size can be got 1.0 when the concrete is sealed. The influence of concrete strength and content of fly ash can be reflected by content of cement.

Tab. 2 shows the evaluation of ACI 209R-92 model is slightly inferior for larger content of fly ash in group III. Because with the increasing of content of fly ash, the content of cement is reduced and the activity of fly ash is general lower, so that the shrinkage of concrete is decreasing. The ACI 209R-92 model is not fully considered.

Based on the test data, a correction factor γ_{fa} is proposed into the shrinkage formula recommended by ACI209 committee, as shown in Eq. (1):

$$(\varepsilon_{sh})_{t-ACI} = (\frac{t}{35+t}) \cdot \gamma_{fa} \cdot (\varepsilon_{sh})_u \tag{1}$$

In which t is time of shrinkage; γ_{fa} is the correction coefficient of fly ash content, as shown in Eq. (2):

$$\gamma_{fa} = -0.5215 k_1 + 1.0264 \quad (k_1 = 0.10 \sim 0.40) \tag{2}$$

$(\varepsilon_{sh})_u$ is the final shrinkage, as shown in Eq.(3):

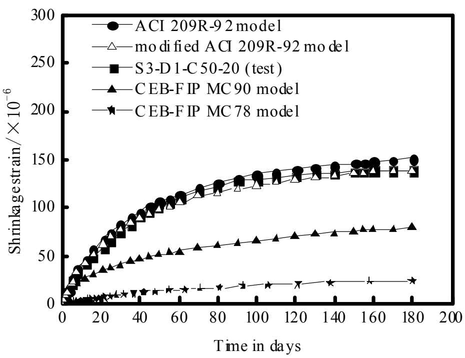
$$(\varepsilon_{sh})_u = (780 \times 10^{-6}) \cdot \gamma_{CP} \cdot \gamma_{\lambda} \cdot \gamma_{vs} \cdot \gamma_s \cdot \gamma_{\psi} \cdot \gamma_c \cdot \gamma_{\alpha} \tag{3}$$

In which, 780×10^{-6} is the free shrinkage strain under standard condition, $\gamma_{CP} \cdot \gamma_{\lambda} \cdot \gamma_{vs} \cdot \gamma_s \cdot \gamma_{\psi} \cdot \gamma_c \cdot \gamma_{\alpha}$ are the correction coefficient by considering the influence of initial curing condition, ambient relative humidity, volume-surface ratio, concrete slump, fine aggregate content, cement content and air content, respetively. The detail formula can be fine in Ref. [16].

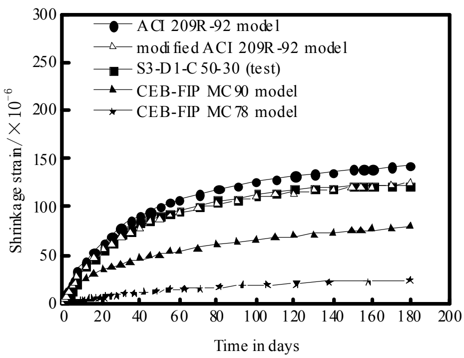
Table 2. *The ratio of predicted value to test at 180d for CFST members.*

No.	Group	Specimen	Measured Strain [$\mu\varepsilon$]	Ratio of Predicted Value to Test			
				ACI 209R-92	CEB-FIP MC90	CEB-FIP MC78	Modified ACI 209R-92
1	I	S1-D1-C50-10	152	1.007	0.526	0.168	0.983
2		S1-D2-C50-10	156	1.045	0.449	0.137	1.020
3		S1-D3-C50-10	165	1.030	0.376	0.102	1.001
4		S1-D4-C50-10	147	1.020	0.190	0.039	0.995
5		S1-D5-C50-10	167	1.000	0.114	0.034	0.976
6	II	S2-D1-C40-10	125	1.096	0.696	0.199	1.067
7		S2-D1-C60-10	168	0.977	0.429	0.152	0.951
8	III	S3-D1-C50-0	165	0.981	0.485	0.155	1.006
9		S3-D1-C50-20	138	1.094	0.580	0.185	1.010
10		S3-D1-C50-30	123	1.163	0.650	0.207	1.013
11		S3-D1-C50-40	108	1.214	0.741	0.236	0.992
		Mean value		1.057	0.476	0.147	1.001
		Variance		0.005	0.035	0.004	0.001

The developmental curve of predicted shrinkage and measured from test for some members is showed in Fig. 6. The results of others are similar and not show in this paper due to the limit space. Fig. 6 and Tab. 2 show the mean value and variance of the ratio of predicted to test for ACI 209R-92 model is 1.057 and 0.005, respectively.



a) S3-D1-C50-20



b) S3-D1-C50-30

Fig. 6. *Comparison between prediction and test for some specimens.*

The parameter of group III is fly ash content. The mean value and variance of the ratio of predicted to test for ACI 209R-92 model is 1.092 and 0.008, respectively. Its evaluation effect is a bit worse than all the specimens. For modified ACI 209R-92 model, the mean value and variance of the ratio of predicted to test is 1.001 and 0.0001, respectively. The prediction accuracy is obviously improved, so are for all the 11 specimens. But the content of fly ash is generally in range of 10% to 20% in the practical engineering, which is in the range of this test (0%~40%). Tab. 2 show the predicted effect is worse when the fly ash content is larger than 20%.

Therefore, the ACI 209R-92 model can still be used to predict the shrinkage when the fly ash content is less than 20%, while it need modify when the fly ash content is larger than 20%. Certainly, the specimens of group III is slightly fewer in this paper. It need further to verify the reasonability of above correction.

3.3. Comparisons between the prediction and other test results

In order to enlarger sample, shrinkage data of 23 CFST specimens from Ref. [1-8] are collected by removing some unreasonable results. The comparisons between the test and prediction by the three models showed that the ACI 209R-92 model is the best one to predict the shrinkage of CFST member. The mean value and variance of prediction-test ratio is 1.180 and 0.215 for ACI 209R-92 model, 0.569 and 0.197 for CEB-FIP MC90 model, 0.252 and 0.030 for CEB-FIP MC78 model.

4. SHRINKAGE STRESS ANALYSIS OF CFST ARCH BRIDGE

The results from section 2 indicate that the ACI 209R-92 model can predict the shrinkage strain of CFST members well. Though it is inferior to predict larger fly ash content, in common used CFST arch bridge the fly ash content is not more than 20% [17]. Therefore, the ACI 209R-92 model is mainly used to analyse the shrinkage effect in this section.

Shrinkage-induced secondary internal force has larger relevant to practical bridge. It is difficult to do general analysis as befored-mentioned shrinkage-induced self-stress. Taken a CFST arch bridge as an exanple, case study for shrinkage-induced secondary stress and self-stress are carried out.

It is a railway CFST arch bridge with a span of 380 m and rise of 77 m, which gives a rise-to-span ratio of 1/5.25. The arch axis is a catenary curve. The bridge has two arch ribs, each one is composed of four CFST tubes. A couple tubes are connected by steel tube web members in vertical direction to form a truss rib, and connected by double steel plates in transverse direction to form upper and lower dumbbell shape CFST chords. The rib is 4 m wide, and the center distance of upper and lower chords varies from 12 m at springing to 6 m at crown. Each of the chord tube has a diameter of 1.5 m with a wall thickness of 30 mm. The bridge’s construction process could be divided into 32 stages in the shrinkage analysis. Other details of the bridge can be found in Li *et al.*[18].

The shrinkage effect of the bridge is analysed by the ACI 209R-92 model, the CEB-FIP MC90 model and CEB-FIP MC78 model, respectively. For ACI 209R-92 model, the concrete slump is 220 mm; Other shrinkage parameters for the three model are the same: the shrinkage age is 3d, environmental relative humidity is 90 %, volume-surface ratio is 1.0 m, the way of curing is moist curing, the concrete strength is C50, the fine aggregate percentage is 39.5 % and the air content is 2.5 %. In order to compare with the equivalent cooling temperature of 15°C is also used to analyse in this case study.

Take the maximum shrinkage-induced stress of steel tube as the analytic target, which is appeared in the lower chord at arch spring section, as shown in Tab. 3.

Table 3. *Shrinkage-induced stress in the lower chord at arch spring section (MPa).*

Model	**Self-Stress**		**Secondary Stress**		**Total Stress**	
	Concrete	**Steel Tube**	**Concrete**	**Steel Tube**	**Concrete**	**Steel Tube**
ACI 209R-92	1.5	-21.8	-0.7	-4.1	0.8	-25.9
CEB-FIP MC90	0.8	-10.9	-0.4	-2.4	0.4	-13.3
CEB-FIP MC78	0.6	-8.6	-0.3	-1.9	0.3	-10.5
Cooling Temperature 15℃	/	/	-0.9	-5.3	/	/

As shown in Tab. 3, all the shrinkage-induced self-stress, secondary stress and total stress calculated by ACI 209R-92 model are larger than CEB-FIP MC90 model and CEB-FIP MC78 model. The shrinkage-induced self-stress calculated by ACI 209R-92 model is tensile stress for concrete infill of 1.5 MPa and the pressure stress for steel tube of 21.8 MPa.

The incremental stress of steel tube caused by self-stress are 84.2%, 82.0% and 81.9% of total stress for the three models, respectively, while the secondary stress are 15.8%, 18.0% and 18.1%. The stress of steel tube and concrete infill caused by self-weight is -92.1MPa and -13.1MPa, respectively. The incremental stress of steel tube caused by shrinkage self-stress is 23.7%, 11.8% and 9.3% of self-weight for the three models, while the secondary stress is 4.5%, 2.6% and 2.1%. Therefore, the analysis indicates that the influence of shrinkage self-stress is larger than secondary stress (is very small, can be neglected).

The result calculated by cooling temperature 15°C is larger than ACI 209R-92 model (it can be equivalent cooling as 13.7°C by this model). It should be point out the equivalent cooling temperature method can't get the shrinkage-induced self-stress, which is larger than the secondary stress.

5. CONCLUSION AND SUGGESTION

(1) Analysis results on predictions of the shrinkage deformation of the specimens by the common shrinkage models indicate that the ACI 209R-92 model could give good prediction results but the deviation will increase when the content of fly ash in the concrete is large. Based on the test results, a modified ACI 209R-92 is presented for the shrinkage of CFST member for concrete with a fly ash content no less than 20%. Shrinkage deformation calculated by CEB-FIP MC90model and CEB-FIP MC78 model for CFST member is obviously lower than test. Both the two models are not used during design calculation.

(2) It is difficult to give out an equivalent cooling temperature value, so the equivalent cooling temperature method is not suggested to be used in design calculation. The shrinkage-induced secondary stress is small and could be ignored in preliminary design, whereas the shrinkage-induced self-equilibrium stress is quite large and should be taken into account in design calculation.

(3) The shrinkage strain of sealed concrete and CFST for common used CFST arch bridges can get 172με to 247με and 78με to 208με, respectively. For the common used Q345 steel tube, the shrinkage self-stress of steel tube is range of 16.1 MPa to 42.8 MPa and up to the range of 4.7% f_y and 19.0% f_y. Therefore, the self-stress caused by

shrinkage must be taken into account during design. But the shrinkage-induced secondary stress is smaller and can be neglected in preliminary estimate.

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