Numerical Simulation on Concrete Pouring Process of Self-Compacting Concrete-Filled Steel Tube

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SUMMARY:
Self-Compacting Concrete (SCC) has been widely used in Concrete-Filled Steel Tube (CFST) structures because of its excellent ability of fluidity. The compactness for the SCC has influences on the durability and bearing capacity of SCC members. However, the flow process of the concrete pouring and the influence factors were less understood for it hid in the steel tube with inconvenient observation. The numerical simulation for the compactness of the SCC column was performed in the paper with computational software FLOW-3D. The fresh concrete was considered as homogeneous fluid, and a 3D Bingham model with two parameters-yield stress and viscosity was used to describe the fluid behavior of the concrete. The casting of the SCC for a CFST column were numerically simulated and compared with the experimental results both in laboratory and in situ. The results showed that the proposed method can clearly show the process of the SCC column.

Keywords: Self-compacting concrete (SCC); Concrete-filled steel tube (CFST); Numerical simulation

1. INTRODUCTION

Many problems of compactness of concrete structures are due to bad filling of formworks. This issue is increasing year after year as formworks are getting more and more complex and reinforcements are getting denser and denser with the use of self-compacting concretes (SCC). Unfortunately, if problems such as segregation of aggregates occur inside the structure, they can’t be detected easily (Gram et al, 2007). This may happen for tortuous formworks and/or around reinforcement bars due to locking problems. Even if no voids are formed during the filling, segregation may still occur which yields a heterogeneous hardened material at the scale of the structure (Barrat et al, 2007). In this case, the durability of the structure may be endangered as transfer properties of concrete are increased. It is therefore of importance to devise numerical tools aimed at the simulation of the filling of formworks with concrete. This paper is a first step toward this goal. It addresses the numerical modeling of concrete flow, assuming that concrete is homogeneous but the material modeling and the numerical method can easily be applied to the simulation of heterogeneous fluids (Sonebai et al, 2007). Self-compacting concrete is a new kind of high performance concrete with excellent ability of fluidity.

Among the difficulties of the simulation of concrete flow, the numerical aspects and the identfication of the concrete rheology parameters are those addressed in this paper where we model fresh concrete as a homogeneous viscous fluid. On the material side, tests, as simple as possible, are required in order to calibrate the model parameters.

Some papers have been discussed the computational or numerical methods for concrete flow during casting. Gilles (2005) used a finite element method with Lagrangian integration points in order to model numerically concrete flow inside formworks like the L-box, and follow in time and space material motion with any type of material behaviour, including non-linear and time independent ones. It also can deal with free surfaces or material interfaces. Bingham’s rheology was used for fresh concrete behaviour. Gram (2009) simulated large volumes of concrete which was modelled as a homogeneous material. Particular effects of aggregates, such as blocking or segregation were not accounted for. Good correspondence was achieved with a Bingham material model used to simulate concrete laboratory tests (e.g. slumpflow, L -box) and form filling. Flow of concrete in a particularly congested section of a double-tee slab as well as two lifts of a multi-layered full scale wall casting was simulated successfully. Gardner and Lockman (2001) presented a design-office procedure for calculating the shrinkage and creep of concrete using the information available at design, namely, the 28-day specified concrete strength, the concrete strength at loading, element size, and the relative humidity.

In the paper, the compactness of the SCC was studied with computational software FLOW-3D. It is because of some of its advantages and strong human-computer interaction that makes it possible to simulate the concrete pouring of self-compacting concrete-filled steel tube. In this process, we can assess the compactness of the SCC explicitly. In the first section, the numerical model was described and the rheological models for concrete were discussed. A real model that was similar to the real one was set up and the parameters of concrete according to the previous research were set, then the process of the pouring of the concrete can clearly be seen. In the second part, the shrinkage of concrete based on the existing prediction models of Gardner-Lockman Model were calculated (David, 2002). Finally, numerical results against experimental results were compared.

The CFST that is mainly studied in this paper is based on the Project of Dagongbao in Anshan. By this means, we can be more accurate to simulate the real situation and then come to an ideal conclusion.

2. NUMERICAL MODELLING

2.1. Validation of Simulation

For the validation of the test, a sample of the SCC was made, based on the got results. The L-Box test was conducted and the parameters related to the flow of the SCC were listed at the same time. The L-Box test was among the standard experiments aimed at measuring concrete workability. Measurements consisted in recording the arrival time at the end of the horizontal part and also the profile of the free surface of concrete in the horizontal part.

For this simulation, the variation for the opening time was negligible in the computations. Boundary conditions were always free-slip and set to symmetry that was default in the software. The only driving force was gravity with a concrete density of 24kN/m^3. The size of the L-Box was referring to the standard of the SCC. Therefore, the model of the simulation was the same as the real one. After that, the process was precisely finished, and then the experiment and the simulation of different time were compared, e.g. see Fig.2.1. Simulations on the L-box experiment, in which a 2D flow was reproduced, were close to the experiments. From the results, it can be found out that the simulation can nearly account for the experiment, such as, the state of concrete, and the position of the concrete. Therefore, the process was valid and it can be used for SCC.

2.2. Setting up Model

2.2.1. Basic assumption

In order to simulate the pouring of concrete by the software, some assumption needs to be made to simplify the problem. Basic assumption is as follow (Hua Lei, 2011):

1) The process of the pouring is continuous that means the velocity of SCC is a constant value.
2) The tube can be completely filled.
3) The SCC has constant viscosity and material density not change with the temperature and time.
4) Bingham's rheology is used for fresh concrete behaviour.
5) Take no account of the heat exchange of SCC.

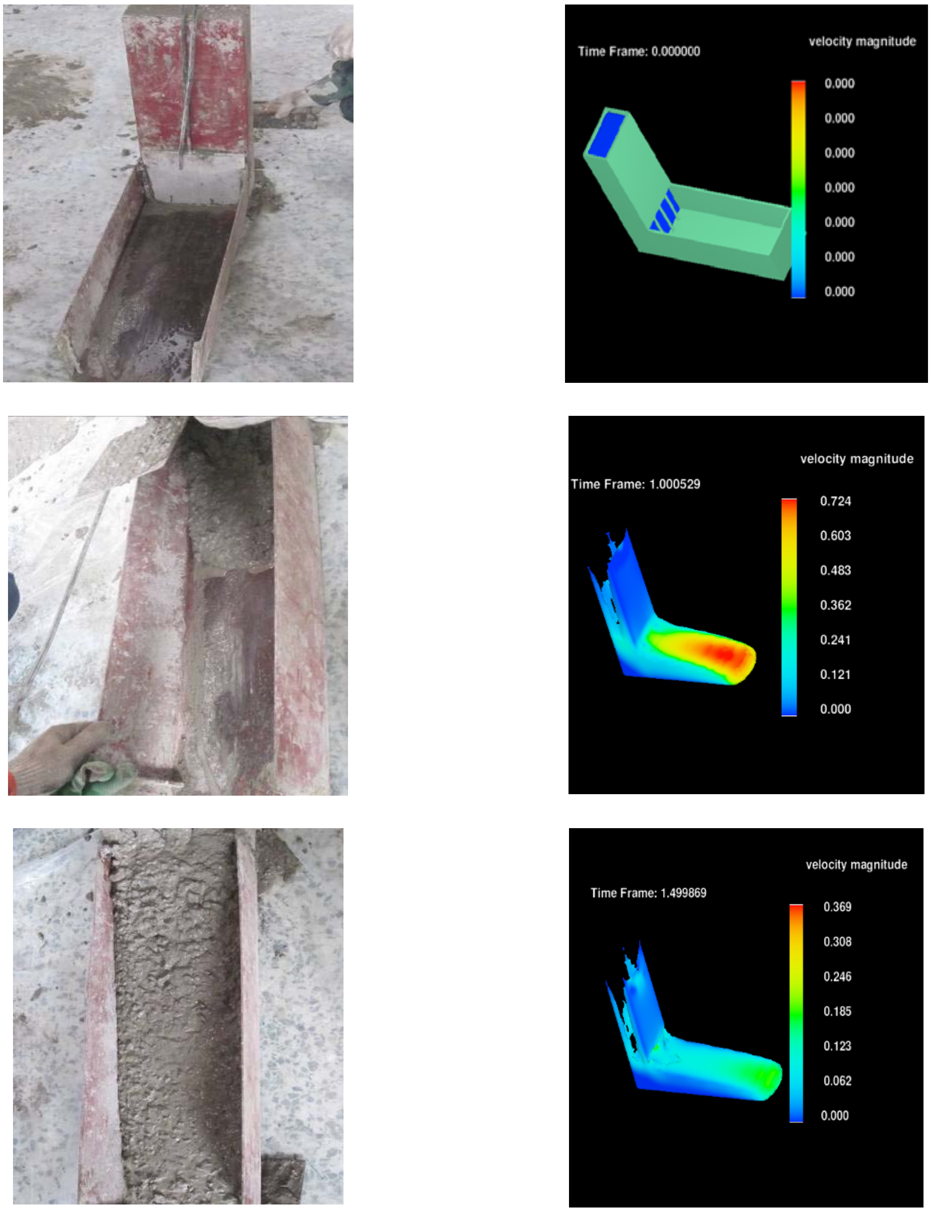


Figure 2.1 Process of L-Box test in Spatial Space

2.2.2. Physical properties of concrete and specimen

In order to avoid the influence of the specimen size, the dimension is nearly the same as the real project. The CFST column specimen studied in the experiment has an outer cross section of 300mm x 300mm and a height of 9000mm, e.g. see Fig. 2.2. The tube contains two clapboards in the vertical axis, the height of 3000 and 6000mm, respectively. The concrete mixture of SCC and properties are presented in Table 1.

Table 2.1. The Concrete Mixture of SCC And Properties

Strength of cement (MPa)	Fly ash levels	Content per cubic meter(Kg)					
		Cement	Fly ash	Sand	Gravel	Water	Water reducer
32.5	I	312	121	782	865	194	4.81

It is known that that the longer the curing time, the less shrinkage will occur. What we paid attention to was that the void mainly existed below the clapboard and both of them were being existence. The size of the void was nearly identical with each other. Therefore, the key of the simulation was the clapboard and a model which contained clapboard located at the height of 3000mm was set up. The thickness of the steel tube was 6mm and the cross section in detail was shown in Fig. 2.3.

Figure 2.2. The CFST specimen

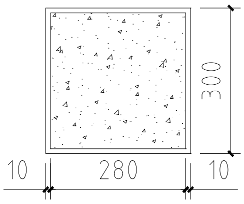


Figure 2.3. Cross section of the CFST specimen

For this simulation, it was the key to determine the size of the computational domain, mesh resolution, and physical models. The tube will be filled with SCC. For the purpose of making the simulation truer, a cylindrical inlet of 1m long and 100mm in diameter on the top of the steel tube was set up, which was combined with the top layer of tube. The model of the tube was shown in Fig. 2.4 and 2.5, respectively.

Figure 2.4. Cutting figure of the model

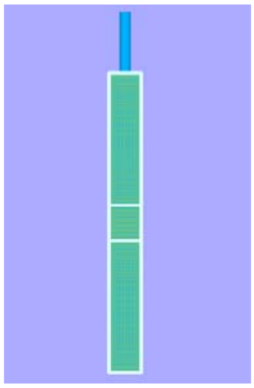


Figure 2.5. Mesh of the model

2.2.3. Binghamton fluid

Concrete flow properties need to be characterized by more than one parameter because concrete is a non-Newtonian fluid. The most commonly-used model is the Binghamton equation that requires two parameters, with one being the yield stress, because it shows an initial resistance to the flow which should not be neglected, and the other one being plastic viscosity that governs the flow after it was initiated. In the Binghamton model, the flow is characterized by the following equation:

$$\tau_0 = \frac{\rho}{347}(S - 256) + 212 \tag{2.1}$$

where ρ is the density expressed in kg/m^3, and S is the final slump in mm.

$$\mu = \rho T (S - 175) \times 1.08 \times 10^{-3}\text{, for 200mm<S<260mm} \tag{2.2}$$

$$\mu = 25 \times 10^{-3} \rho T\text{ , for S<200mm} \tag{2.3}$$

Where μ is the viscosity in Pa.s and T is the slumping time in seconds (Chiara, 2010).

Now we need to determine the two parameters through the slump test, e.g. see Fig. 2.6.

Figure 2.6. The Slump test

Through the test, the *S* of the SCC can be obtained, *S*=256mm, *T*=1.5s; So,

$$\tau_0 = \tfrac{2400}{347}(300-256)+212 = 516\text{Pa}$$
$$\mu = 2400\times1.5\times1.08\times10^{-3}\times(256-175) = 315\text{Pa}\cdot\text{s}$$

2.3 Parameters of Simulation

During modelling for the SCC, the driving force for flow of concrete was only gravity with a concrete density of 24kN/m^3. Then, the concrete is regarded as Binghamton and its viscosity properties need to be specified since the viscous forces are significant. Here, the gravity and viscosity and turbulence model were chosen as the physical model and strain-rate dependent viscosity.

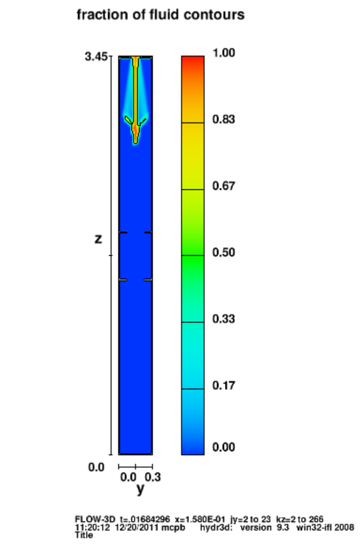
During meshing for the finite element analysis, it was first necessary to determine the size of the computational domain. The primary goal of the simulation was to simply fill the tube as a minimum. The computational domain needed to include the entire tube. The dimensions of the tube were displayed in the Fig.2.3. In order for the software to better identify the slice of the tube, it should be outside of the mesh block. The mesh block will be divided into lots of cells. Now, there were two options for meshing. One option was to specify the total number of cells in the mesh block and the other option was to specify the size of all cells in the mesh block. Considering the clapboard of the tube, which was the thinnest, and the computing time, the minimum cell size of 10mm and the maximum cell size of 15mm were set up, and the XY, YZ, and XZ direction maximum aspect ratios were limited in 1.60952.

3. RESULT OF SIMULATION

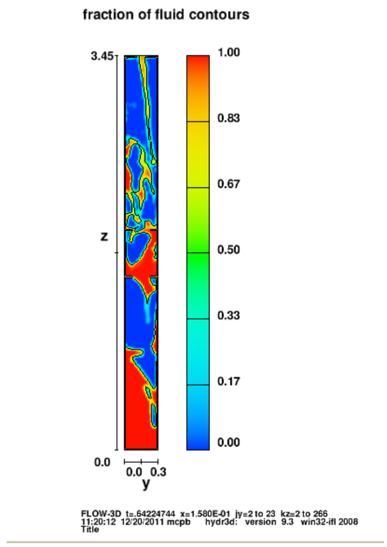
After the simulation, the whole process of the pouring of the concrete was got. The numerical results showed that several typical stages of the concrete were as follow, e.g. see Fig. 3.1. From the four figures as follow, we can verify the initial stage, the middle stage and the final stage in the x-z plane. The fraction of fluid contours of concrete can present the position of the concrete in the process at different time. Because the flow of the concrete, we can from Fig.3.1(c) that some void was existence. As the filling time went on, the tube was absolutely filled due to the gravity in the end. This is in line with the actual situation.

4. COMPARISON OF SHRINKAGE BETWEEN TEST AND SIMULATION

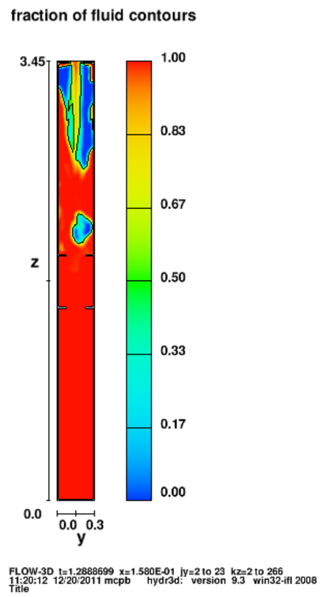
Concrete is an age stiffening material that will shrink in any environment with a relative humidity below hydro equilibrium-the relative humidity at which concrete neither shrinks nor swells. Thus, autogenously shrinkage of low water-cement ratio (w/c) high-strength concrete is a problem. Factors which contribute to the dimensional changes in concrete may be categorized as mixture composition, curing conditions, ambient exposure conditions, and element geometry.



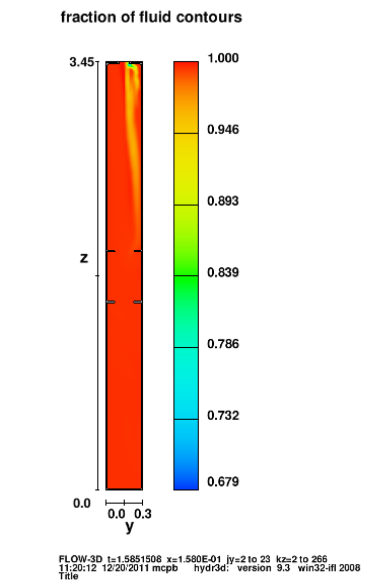
(a) t=0.168s



(b) t=0.642s



(c) t=1.289s



(d) t=1.585s

Figure 3.1. Fraction of concrete at different time on x-z plane

The model was developed to estimate shrinkage and compliance for normal-strength concretes that are defined as concretes with 28-day mean compressive strengths less than 82 MPa (concrete characteristic strength of 70 MPa) and w/c between 0.40 and 0.60.

Shrinkage can be estimated using the following equation.

$$\varepsilon_{sh} = \varepsilon_{shu} \beta(h) \beta(t) \tag{4.1}$$

$$\beta(h) = \left(1 - 1.18h^4\right) \tag{4.2}$$

$$\varepsilon_{shu} = 1000 \times K \cdot \left(\frac{30}{f_{cm28}} \right)^{1/2} \times 10^{-6} \tag{4.3}$$

$$\beta(t) = \left(\frac{t - t_c}{t - t_c + 0.15 \cdot (V/S)^2} \right)^{0.5} \tag{4.4}$$

Where, h = humidity expressed as a decimal;
t = age of concrete, days;
t_c = age drying commenced, end of moist curing, days;
K = 1 Type I cement; K = 0.70 Type II cement; K = 1.15 Type III cement;
V/S = volume-surface ratio, mm;
$f_{cm,\,28}$ = concrete mean compressive strength at 28 days, MPa;
ε_{sh}= shrinkage strain;
ε_{shu}= notional ultimate shrinkage strain.

For TYPE I cement is general purpose cements suitable for all uses where the special properties of other types are not required. So K=1, t=7, t_c=100, h=0.5, V/S=300/4,
and $f_{cm,\,28}$=39.

$$\beta(h) = \left(1 - 1.18h^4\right) = 0.92625$$

$$\varepsilon_{shu} = 1000 \cdot K \cdot \left(\frac{30}{f_{cm28}} \right)^{1/2} \cdot 10^{-6} = 1000 \cdot 1 \cdot \left(\frac{30}{39} \right)^{1/2} \cdot 10^{-6} = 870 \cdot 10^{-6}$$

$$\varepsilon_{sh} = 870 \cdot 0.92625 \cdot \left(\frac{100 - 7}{100 - 7 + 0.15 \cdot (300/4)^2} \right)^{0.5} \cdot 10^{-6} = 270 \cdot 10^{-6}$$

Because of the gravity, and concrete in intermediate continuous, all around disconnect, there the shrinkage crack is become wider from inside to out and approximation of a linear change. So when estimating the shrinkage crack of the concrete, we take the average of the maximum and minimum. Here, the maximum ε_{sh} measured is $350 \cdot 10^{-6}$, and the minimum ε_{sh} measured is $210 \cdot 10^{-6}$. So the average shrinkage crack is $280 \cdot 10^{-6}$, meanwhile the error is 3.7%.
The shrinkage of the concrete is shown in Fig. 4.1.

Figure 4.1. The shrinkage below the clapboard of the tube

5. CONCLUSION

Concrete flow properties need to be characterized by more than one parameter because concrete is a non-Newtonian fluid. The most commonly-used model is described by the Bingham equation that requires two parameters, i.e., yield stress and the plastic viscosity. Through the slump test, the two parameters are got, which are utilized to describe the SCC, and the simulation for the L-Box test gives a real reaction of the results.

Based on the above conclusion, we know that it is reasonable of the numerical simulation for the flow of concrete. Therefore, a model is set up to simulate the process of the pouring and it is also clearly in comparison with real situation. This will do a good favor for the predetermination of the pouring process. Hence, it will save us a lot of time and energy to do plenty of tests for the purpose of observation. At last, a shrinkage model which is suitable for the SCC is chosen to calculate the shrinkage strain after the 100 days in the curing condition. The error between the theoretical value and the test one is about 3.7%, which is acceptable in error range. At the same time, it also tells us that this method is feasible.

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