# Simulation of Corrosion Process for Structure with the Cellular Automata Method

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**Abstract.** In this paper, from the mesoscopic point of view, under the assumption of metal corrosion damage evolution being a diffusive process, the cellular automata (CA) method was proposed to simulate numerically the uniform corrosion damage evolution of outer steel tube of concrete filled steel tubular columns subjected to corrosive environment, and the effects of corrosive agent concentration, dissolution probability and elapsed etching time on the corrosion damage evolution were also investigated. It was shown that corrosion damage increases nonlinearly with increasing elapsed etching time, and the longer the etching time, the more serious the corrosion damage; different concentration of corrosive agents had different impacts on the corrosion damage degree of the outer steel tube, but the difference between the impacts was very small; the heavier the concentration, the more serious the influence. The greater the dissolution probability, the more serious the corrosion damage of the outer steel tube, but with the increase of dissolution probability, the difference between its impacts on the corrosion damage became smaller and smaller.To validate present method, corrosion damage measurements for concrete filled square steel tubular columns (CFSSTCs) sealed at both their ends and immersed fully in a simulating acid rain solution were conducted, and Faraday's law was used to predict their theoretical values. Meanwhile, the proposed CA mode was applied for the simulation of corrosion damage evolution of the CFSSTCs. It was shown by the comparisons of results from the three methods aforementioned that they were in good agreement, implying that the proposed method used for the simulation of corrosion damage evolution of concrete filled steel tubular columns is feasible and effective. It will open a new approach to study and evaluate further the corrosion damage, loading capacity and lifetime prediction of concrete filled steel tubular structures.

## 1. Introduction
Concrete filled steel tube (CFST) has been widely used in high-rise building, bridge, high voltage transmission tower, oil drilling platform and offshore structure and other engineering structures owing to its excellent mechanical properties [1]. However, since long-term exposure to air or seawater, the outer steel tube is vulnerable to aggressive agents like acid rain, ocean climate, sea water and so on. As etching time goes, there will be large area corrosion and losing on the surface of outer steel tube, decreasing the rigidity of CFST structure, role of combined action and degradation of structural resistance, and thereby affecting its service life, that is durability and safety. On the study of the mechanical performances of CFST structures in corrosive environment, many experimental researches have been carried out [2, 3]. Nevertheless, none of these studies takes into account that the environmental corrosion damage process is a complex dynamic system and the degradation of structural resistance is time-dependent. Although many scholars have used the Monte Carlo [4] and Cellular Automata method [5,6] to study the damage evolution process of localized corrosion on steel

structure, none of them focused on corresponding simulation researches on the uniform corrosion damage evolution process of steel structure. Therefore, study on the simulation of uniform corrosion damage evolution process for the CFST structure in the aggressive environment is of theoretical value and practical significance. Due to many influencing factors in environment, corrosion damage can not be accurately measured [7]. As an effective tool to research complex nonlinear system and non-uniform dynamic system, the cellular automata method has better universal property and stability in simulating the corrosion damage evolution process.
In this paper, a two-dimensional cellular automata (CA) model will be used to simulate uniform corrosion damage evolution process of CFST in corrosive environment. The influence of solution concentration and dissolution probability of corrosive agents is discussed. As a benchmark example, the model is used to simulate the process of corrosion damage of outer steel tube of CFST under acid rain environment. Present simulation is compared with theoretical solutions and experimental results.

## 2. The model of cellular automata

### *2.1 Composition*

Cellular automata (CA) is a complex dynamic system which is discrete in time and space [8]. It consists of cellular, neighbor, space, status, local evolution rule, initial conditions, boundary conditions and so on [9]. Figure 1 shows the relationships among them.

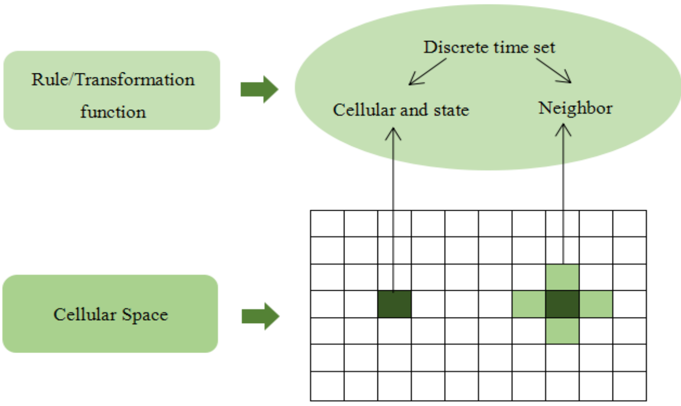


**Figure 1.** Schematic diagram of cellular automata composition

Cellular is the most basic component of cellular automata. Neighbors in two-dimension cellular automata have many forms, three common types of them are Von Neumann, Moore and Extended Moore. The local evolution rule is a dynamic function, which determines the state of central cell at next moment from the state of central cell and its neighbors at present moment. It is also called the state transition function expressed as in the following:

$$C_i^{t+1} = \varphi(C_i^t, C_{i,1}^t, C_{i,2}^t, \cdots, C_{i,j}^t, \cdots, C_{i,n}^t) \quad (1)$$

Where $C_i^{t+1}$ is the state of central cell $i$ at next moment $t$+1, $C_i^t$ is the state of central cell $i$ at current moment $t$; $C_{i,j}^t$ indicates the state of cellular neighbor $j$ at current moment $t$; $\varphi$ is local evolution coefficient, and $n$ is the number of neighbors around central cell. Boundary conditions are used to determine the special physical characteristics of the system during simulation process, and four types of boundary conditions are usually periodic, fixed, adiabatic and reflection. In this paper, the periodic boundary condition was adopted.

### *2.2 Local evolution rule*

The metal and etchant solution space are discretized in CA model, and the dynamic characteristics of metal corrosion are described through the evolution rules of cellular state at discrete time. In this paper, the system is composed of metal and etchant solution, and it is divided into a 1000 × 1000 ordered cellular grids, as shown in Figure 2. Among them, A and B represent corrosive and non-corrosive cell, respectively, which they have direction, also can randomly spread. They are used to simulate diffusion process in electrolyte system. Solution concentration *c* is determined by the ratio of A/B. M representing the metal cell, it can be corroded by A, and cannot move at will during simulation process. A and B can occupy the cell position of M at will.

| | | | | | |
|---|---|---|---|---|---|
| A | B | A | B | A | B |
| B | A | B | A | B | A |
| A | B | A | B | A | B |
| M | M | M | M | M | M |
| M | M | M | M | M | M |
| M | M | M | M | M | M |

**Figure 2.** Cellular grid

According to the above local reaction rules along with MATLAB software programming, the corrosion damage simulation under different conditions is carried out.

*2.3 Characterization of corrosion damage*

The shape of metal surface will change with time. After a period of time, uneven pattern on the surface has been formed. For uniform corrosion, the method of characterizing the degree of corrosion are usually based on corrosion weight, depth, and current density. From the engineering application point of view, the effective section size of corroded components is an important index to reflect the life and safety of structure or equipment. Therefore, it is more practical to characterize the extent of corrosion by the corrosion depth method. The etch depth can be expressed as the ratio of *N(t)* (total number of metal cells which are corroded during *t* (time)) over *M(t)* (which is the number of metal cells inside each layer of cells), that is,

$$H(t) = N(t) / M(t) \tag{2}$$

Where *M(t)* in present paper is set to be 1000.

## 3. Comparison of simulation results with theoretical prediction and experimental results

In terms of the equivalent corrosion depth method, this paper defines the overall height of the metal cell M equal to 3.640mm in thickness of experimental steel tube, and thus the length of single metal cellular is 3.64/5000=0.00728mm. The simulation time step t=100 is equivalent to the actual corrosion time of one week during the simulation process. Due to consideration of the influence of gravity, when defined the direction of solution cellular, the probability that cellular moves to the left and the right is 1/4, respectively and the ratio of the probability that cellular moves to upward over downward is 1:9. The corrosion depth on the surface of concrete filled steel tube (CFST) under acid rain attack was predicted by using the cellular automata model based on the above local transition rules, with concentration *c*=0.1, 0.3, 0.5, 0.7 and dissolution probability *p*=0.1, 0.3, 0.5, 0.7, 0.9, respectively. The curves of time-dependent corrosion thickness under different dissolution probability when *c*=0.1 and the curves of time-dependent corrosion thickness under different solution concentration when *p*=0.1 were obtained, as shown in Figure 3 and Figure 4.

Figure 3 and Figure 4 indicate that the corrosion depth of outer steel tube wall with the variation of etching time is stable after second weeks either for different dissolution probabilities or different solution concentrations.

Comparing the data when solution concentration *c*=0.1 and dissolution probability *p*=0.1 with theoretical predictions by the Faraday's first law [10] and experimental results. The thicknesses of steel tube at different etching time are shown in Table 1, the curve of time-corrosion depth of the outer steel tube each week and the curve of time- thickness of the outer steel tube are shown in Figure 5 and Figure 6.

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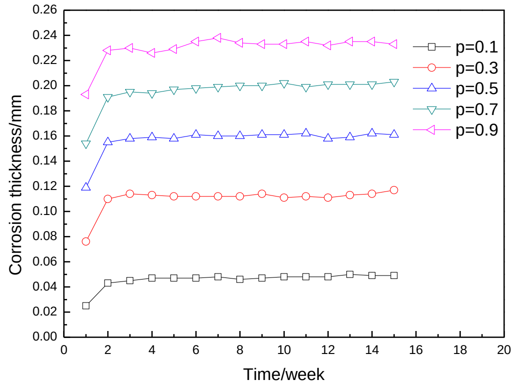


**Figure 3.** The curve of time-dependent corrosion thickness under different dissolution probability

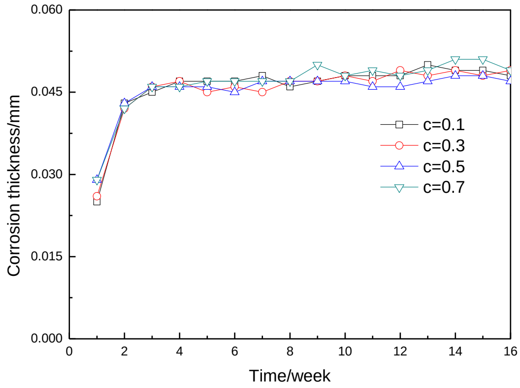


**Figure4.** The curve of time-dependent corrosion thickness under different solution concentration

**Table 1.** Chart of steel thickness date (unit: mm)

| Time/week | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| theoretical wall thickness | 3.640 | 3.595 | 3.550 | 3.505 | 3.460 | 3.415 | 3.370 | 3.325 | 3.280 |
| measured wall thickness | 3.640 | 3.599 | 3.556 | 3.512 | 3.467 | 3.421 | 3.374 | 3.327 | 3.280 |
| simulated wall thickness | 3.640 | 3.615 | 3.572 | 3.527 | 3.480 | 3.433 | 3.386 | 3.338 | 3.292 |
| weekly theoretical corrosion depth | 0.000 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 |
| weekly measured corrosion depth | 0.000 | 0.041 | 0.043 | 0.044 | 0.045 | 0.046 | 0.047 | 0.047 | 0.047 |
| weekly simulated corrosion depth | 0.000 | 0.025 | 0.043 | 0.045 | 0.047 | 0.047 | 0.047 | 0.048 | 0.046 |

| Time/week | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | |
|---|---|---|---|---|---|---|---|---|---|
| theoretical wall thickness | 3.235 | 3.190 | 3.145 | 3.100 | 3.055 | 3.010 | 2.965 | 2.920 | - |
| measured wall thickness | 3.232 | 3.184 | 3.136 | 3.087 | 3.036 | 2.985 | 2.935 | 2.882 | - |
| simulated wall thickness | 3.245 | 3.197 | 3.149 | 3.101 | 3.051 | 3.002 | 2.953 | 2.905 | - |
| Weekly theoretical corrosion depth | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | - |
| weekly measured corrosion depth | 0.048 | 0.048 | 0.048 | 0.049 | 0.051 | 0.051 | 0.050 | 0.053 | - |
| weekly simulated corrosion depth | 0.047 | 0.048 | 0.048 | 0.048 | 0.050 | 0.049 | 0.049 | 0.048 | - |

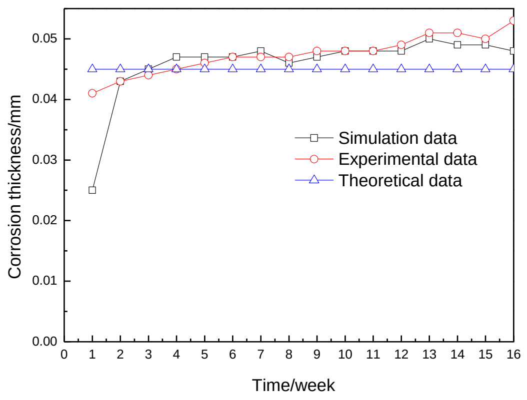


**Figure 5.** Time-dependent average corrosion thickness

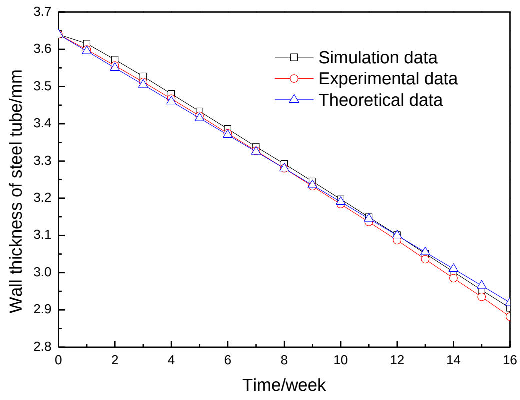


**Figure 6.** Time-dependent thickness of steel tube wall

From Table 1, Figure 5 and Figure 6, we can see that the curves of the variation of surface depth of CFST simulated with the CA model agree well with the theoretical curve and the experimental curve. The corrosion depth at previous weeks is slightly less than that of the theoretical corrosion depth, because there is a piece of passivation film on the surface. As etching time increases, the corrosion depth of the week is lightly higher than the theoretical corrosion depth. To a certain extent, it also confirms the Faraday first law.

## 4. Conclusion

This paper has established a model of uniform corrosion damage evolution on metal surface based on the cellular automata (CA) method, considering several factors such as the initial solution concentration, etching time, and dissolution probability et al, and examined the evolution of corrosion damage. In addition, the process for corrosion damage evolution on the surface of CFST under acid rain environment has been simulated. Theoretical predictions and experimental results are used to confirm the model. Based on the basis of above studies, the following conclusion can be drawn:

First of all, the corrosion depth increases with increasing etching time. Secondly, as the dissolution probability rises, the relationship between corrosion depth and etching time is increased. Thirdly, although the average corrosion depth was slightly changed with the increase of the solution concentration, on the whole, the difference among the effects of solution concentration on the corrosion depth is not large. Besides, the corrosion depth of the outer steel tube wall with the increase of etching time is stable after second weeks either for different dissolution probability or different solution concentration. What’s more, it is feasible and effective to use the CA model to simulate the corrosion depth of CFST under acid rain attack. By defining different local evolution rules and changing the parameters in the simulation process, the CA model could be applied to the study of process for corrosion damage evolution of metal materials in aviation, petrochemical and nuclear power and other fields.

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