ANALYTICAL EVALUATION ON STRUCTURAL SEISMIC PERFORMANCE OF CORRODED RC COLUMNS SUBJECTED TO HIGHER AXIAL COMPRESSION

K.SHIBATA[1], S.HOMMA[2], N.CHIJIWA [3†], K.MEAKAWA[4]

[1, 2, 4]*Graduate School of Engineering, University of Tokyo, Japan*

[3]*Graduate School of Science and Engineering, Tokyo Institute of Technology, Japan*

ABSTRACT

Corrosion on reinforcing bars in concrete causes deterioration of structural performance in RC structures. Past research revealed several mechanisms of corrosion occurrence and structural performance at each corrosion condition. However, none of this research could evaluate the future structural performance of RC structures with corrosion based on existing conditions, due to the complexity of material-structural interactions on corrosion progress which are impossible to calculate without considering concrete hysteresis. Based on past research, an analytical system, which can consider these phenomena, DuCOM-COM3 has been developed. Using the analytical system, a past experiment with a corroded column has successfully been reproduced. After the confirmation of the applicability of this analysis to an existing RC member, analysis on several other members and structures was conducted. Examining the result, several features of deterioration unique to each structure were found.

Keywords: Corrosion, Material-structural interaction, Seismic performance, Multi-scale modeling

1. INTRODUCTION

Corrosion on reinforcement is one of the main deterioration mechanisms of RC structures. Owing to its effect on structural safety, corrosion of RC has been studied for decades. This research was mainly aimed at revealing the mechanism of corrosion production and predicting structural performance of RC cracked due to corrosion. However, this research cannot be applied to practical structural management. Corrosion of RC includes complex interactions of chemical reaction and structural behaviors. For example, corroded reinforcement induces cracks along the reinforcement, and corrosive substances pass through the cracks, causing more severe corrosion. Not being able to consider the mutual interaction of chemical reactions and structural behaviors, past research could not evaluate future structural performance based on current conditions of the structure, which is the most important factor for practical maintenance of RC structures.

* Corresponding author: Email: k_shibata1991@concrete.t.u-tokyo.ac.jp

† Presenter: Email: chijiwa@cv.titech.ac.jp

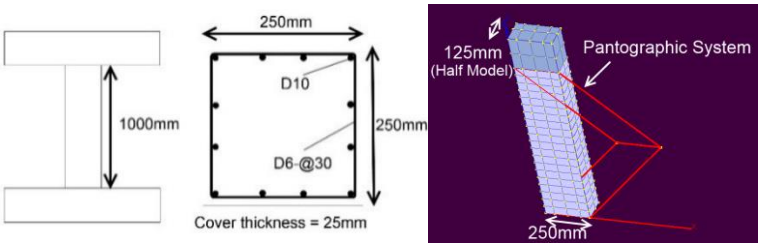

Figure 1: Design of the column.

By coupling the thermodynamic integrated computational system and the structural computational scheme, named as DuCOM-COM3, which can consider interaction of movement of substance and chemical reaction and structural behaviors, has been developed in the University of Tokyo. Upgrades based on recent studies have enabled DuCOM-COM3 system to follow the progress of corrosion from its occurrence to its effect on future structural performance. The authors conducted several analytical simulations by using upgraded DuCOM-COM3 and investigated its applicability for existing RC members, and also observed some feature of corrosion on several RC columns with different designs.

2. ANALYTICAL SYSTEM 'DuCOM-COM3'

As stated in Chapter 1, DuCOM-COM3 is an analytical platform that couples the thermodynamic integrated computational system (DuCOM) with the structural mechanics modeling (COM3). DuCOM is an FE analysis based computational program designed to evaluate various durability properties of concrete, tracing hydration, hardening, micro-pore structure formation, diffusion and transportation of ions and gases. COM3 is also an FE analysis-based computational system, which traces structural behavior of concrete such as cracking, plastic deformation, deformation after cracking, creep, and relaxation. Based on recent studies, several models related to corrosion calculation have been developed, such as models of the stress-strain relationship of RC with cracks along reinforcing bars or models of chloride ion and oxygen penetration and diffusion in concrete.

3. ANALYTICAL SIMULATION OF RC COLUMN EXPOSED AT THE COAST

To verify the reliability of this analytical system, the authors simulated the experiment with a corroded column reported by Arasato *et al.* (2003). The experiment took place at the coast of Okinawa where strong sea wind blows with airborne chloride and the temperature is generally high. The columns () were exposed to such an environment for 4 years, and after the exposure alternate loading tests were conducted. In the loading test, the columns were subjected to a high vertical load, and an alternating horizontal load.

In the analysis, an FE mesh (**Figure 1**) was used. The mesh size was decided such that it fulfilled the model's requirement, in specific the applicability of average stress-strain relationships, and sufficient fineness for accurate calculation. In order to keep the bottom and the top surfaces horizontal, a pantographic system was added using line elements which transfer only vertical force.

Table 1: Environmental inputs

External temperature (℃)	External Rrlative humidity (%)	Pore solution of chloride ion on the surface (g/L)	pore solution of Oxygen on the surface (mol/L)
20	60~99.99 (alternate immasion once a day)	0~2.36 (linearly increases)	9.E-06

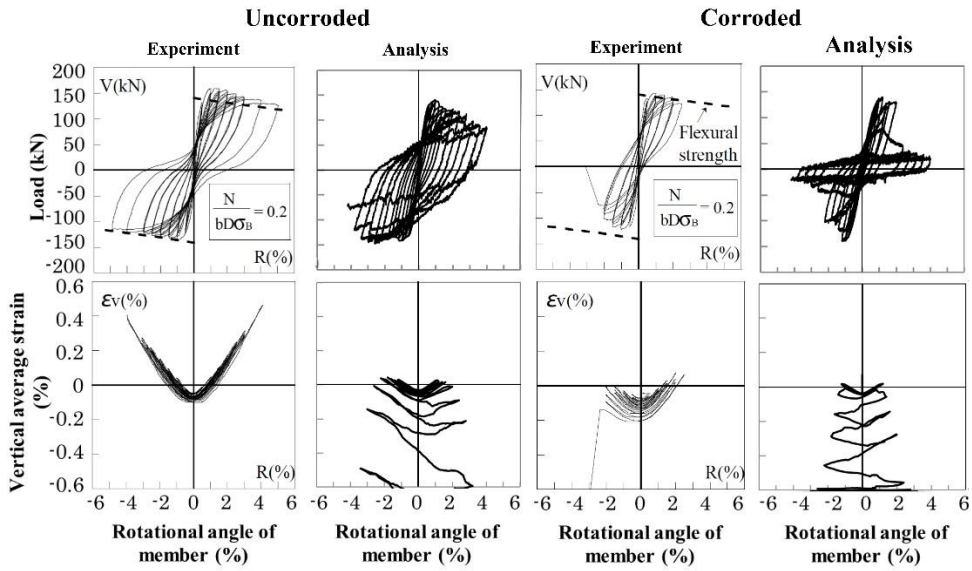

Figure 2: Comparison of results of loading on experiment and analysis.

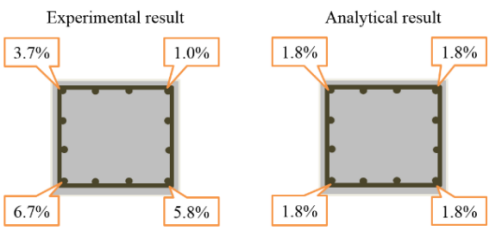

Figure 3: Comparison of average mass loss of reinforcing bars at each point.

In the experiment, there was no environmental input data such as temperature, relative humidity and airborne chloride. However, there are some commonalities in coastal environments, and environmental inputs were set () based on the common environment and experimental data of chloride content in the specimen.

Figure 2 shows a comparison of the result of loading tests both experiment and analysis for uncorroded and corroded specimens. The authors cited the experimental result in the figure (Arasato *et al.* 2003). For the uncorroded specimens, experiment and analysis correspond in almost all aspects. The horizontal axis represents rotational angle of the column, and the vertical represents the reaction force in the horizontal direction. There is a slight difference in the vertical mean strain. This may be explained by a concentration of compressive stress on the bottom of the column due to rigid restraints. The rigid restraint doesn't allow the bottom element to sink any further, and instead of sinking, the element is subjected to a concentrated compressive stress and shrinks.

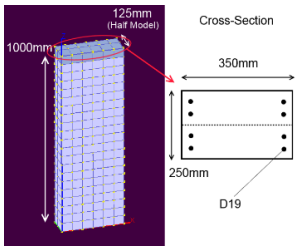

Figure 4: Design and mesh of column.

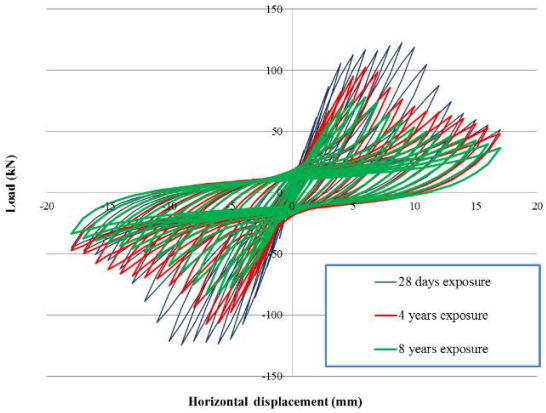

Figure 5: Changing structural performance due to corrosion.

For the corroded specimens, there is some agreement and disagreement between experiment and analysis. The most notable disagreement is in the corrosion distribution along reinforcing bars. The distribution of corrosion was not uniform in the experiment; there were some cross-sections with over 20% mass loss of reinforcing bars, while the average mass loss in reinforcing bars is 5%. There was also uneven distribution in the horizontal direction.

Figure 3 shows a comparison of analytical and experimental results of the average mass loss ratio in reinforcing bars at each location. The authors concluded that environmental input must be major reason of this disagreement. At real coasts, complex wind, the washing out effect of rain, and the direction of sunlight most likely create an un-uniform environment. Due to the lack of data, analysis could not consider such un-uniform environmental input, which is the probable cause. Although these differences exist, the R-V relationship and R-ε_v relationship coincide for the most part. In **Figure 2**, reduction in maximum load, reduction in stiffness and change of failure mode from bending to bending-shear fracture due to corrosion can be observed. Also, extra shrinkage is observed compared to the uncorroded specimen in both the experiment and the analysis.

4. STRUCTURAL PERFORMANCE OF CORRODED RC COLUMNS WITHOUT WEB REINFORCEMENT

The structural performance of corroded RC columns without web reinforcement at several stages of corrosion was simulated with DuCOM-COM3. The detailed design and the FE mesh of the column is shown in **Figure 4.**

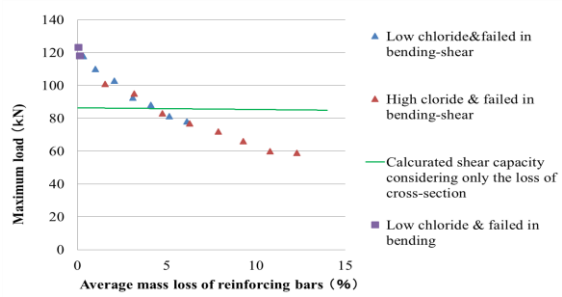

Figure 6: Relationship of maximum load and mass loss of reinforcing bars.

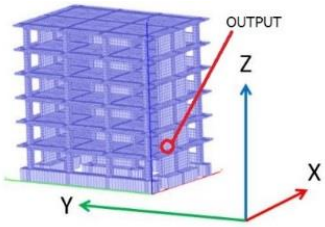

Figure 7: FE mesh.

The analytical results are shown in **Figure 5**. While the column at a progressed stage of corrosion failed in shear before bending, the column at an early stage of corrosion failed in shear after bending. **Figure 6** shows shear and bending capacity correspond to corrosion rate. The markers represent the analytical result; specifically, the square markers are those that failed in bending and the triangular markers are those that failed in shear. The green line represents shear capacity calculated with the JSCE formula considering only the mass loss of the reinforcement as a cause of reduction in shear capacity. From the Figure, the reduction of shear capacity in FE analysis is much larger than that calculated in the formula. The analysis traces not only the loss of reinforcement but also cracking as a cause of structural deterioration by corrosion, while the calculation using the formula only considers the loss of reinforcing bars. The large reduction in shear capacity in the analysis likely comes from cracking rather than loss of reinforcement.

5. BUILDING SCALE ANALYSIS WITH CORROSION

Applying the result of numerical analysis of RC beams and columns with steel corrosion, the authors conducted analysis of real-scale structure. First, the authors numerically reproduced a shaking experiment of a building. Second, with the assumption that the steel in columns and walls is corroded, the authors analyzed how the seismic response changes.

The authors referred to a shaking table test of six-story RC building conducted in "E-defense" Kobe as input acceleration data (Matumori *et al.* 2008). The building has a mass of about 1,000 ton and has 12 columns. The test was conducted with wave data from the Kobe earthquake. In this experiment, the condition of the ground was not considered and the building was directly fixed to the shaking table. Analysis mesh was made precisely in accordance with the building's design (**Figure 7**). All bottom-level nodes are restricted in X-Y-Z direction.

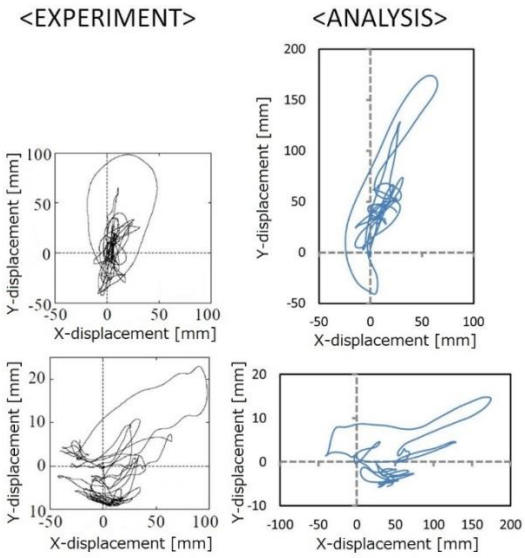

Figure 8: Comparison of experimental and analytical result.

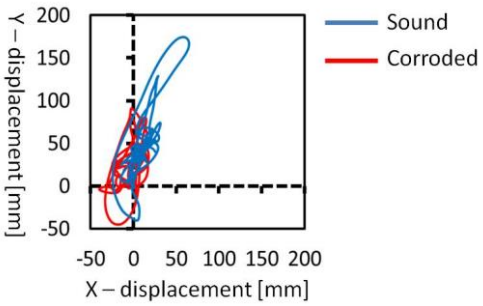

Figure 9: analytical result with corrosion.

Figure 8 shows the comparison of experiment and analysis. The authors cited the experimental result in the figure (Matumori *et al.* 2008). The upper figure shows the 2nd floor's displacement (see **Figure 7**) in the horizontal (X-Y) direction. The bottom figures show the Y-Z displacement. Although imperfect, motion of the building could be essentially reproduced.

In the analysis, the authors introduced corrosion in the columns and walls on the outside of each floor to simulate the severe effects of the surrounding environment. The mass loss due to corrosion was set to 30%. In this case, it was assumed that the building had been in service for decades in a very harsh environment causing progressive corrosion. **Figure 9** is the result of this analysis. The authors inputted 4 sets of seismic data, representing 10%, 25%, 50%, and 100%-amplitude of the seismic data recorded during the Kobe earthquake. During the shaking simulation, plastic damage accumulated in the structure. **Figure 9** shows the result of 100% acceleration. Under smaller accelerations, the building with steel corrosion swayed much larger extent than the un-corroded one. However, with 100% acceleration, the difference between response of sound structure and the corroded one became small.

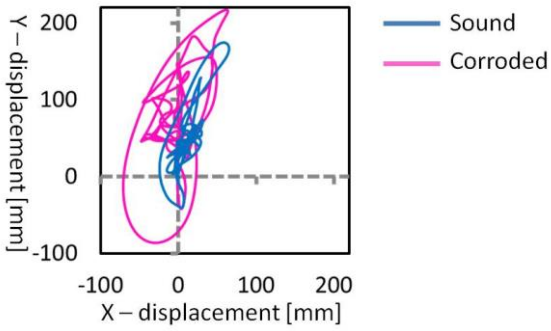

Figure 10: analytical result with 1st floor corroded.

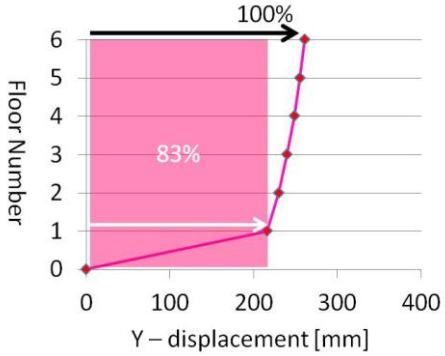

Figure 11: Y-directional displacement of each floor.

Additional analysis of the building was conducted in which only the 1st floor's columns' steel was corroded. The result is shown in **Figure 10**. The 2nd floor's displacement with steel corrosion was found to be smaller than the un-corroded case. **Figure 11** shows the peak Y-displacement. Most deformation took place in the 1st floor (83%). This value is 53% in the un-corroded case and 30% in the case where all floors are corroded. The damage was concentrated in the 1st floor because the upper floors were un-corroded and so stiff that they wouldn't comply with the deformation of the overall structure.

The authors confirmed that numerical analysis of RC structure with steel corrosion is possible. So far, it is difficult to say exactly how dangerous buildings with steel corrosion are. But the authors found that in particular structures, partial damage can be more dangerous than full damage. Additional analysis of various structures using different earthquake waves will be necessary in future.

6. CONCLUSION

The simulation conducted here of a past exposure test of an RC column suggests that the current analytical system DuCOM-COM3 is capable of tracing deterioration story to some extent. Although there are still some unexplained deterioration mechanisms, such as loss of bond due to deformation and changing quality of reinforcing bars, the analytical system is capable of tracing structural deterioration mainly caused by cracks accompanied by corrosion.

Conducting several analyses, several decaying features were suggested:

(1) The reduction of shear capacity of RC columns without web reinforcement is mainly explained by the crack effect rather than the loss of cross-section of reinforcing bars. Further research is needed to reveal the structural decay mechanisms.

(2) Comparing structural performance of corroded RC columns with and without web corrosion, the effect of corrosion of web reinforcement on horizontal stiffness was found to be large. This phenomenon could be a serious concern for the seismic response of aged structures.

(3) Corrosion on structure can improve seismic performance in some cases. However, there are many complex factors such as corrosion state, corrosion location, seismic amplitude, seismic pattern, and it was impractical to analytically investigate them all in this study. Further research is needed to quantitatively identify their contribution to deterioration by corrosion and evaluate the effect of this corrosion on structures.

7. ACKOWLEDGEMENT

The authors received acceleration data of the Kobe earthquake from K-NET.
(http://www.kyoshin.bosai.go.jp/kyoshin/).

REFERENCES

Arasato, Y., Yamakawa, T., Morishita, Y. and Tamaki, Y. (2003). Experimental research on seismic performance of RC column damaged by exposure. *Proceedings of JCI*, vol.25, No. 2, pp. 259-264.

Matsumori, T., Kabeyazawa, T., Shirai, K. and Igarashi, K. (2008). Shaking Table Test on a Full-scale, Six-story R/C Building Structure, Special Project for Earthquake Disasters Mitigation in Urban Areas in 2005 Improvement of Seismic Performance of Structures by E-Defense. Technical Note of the National Research Institute for Earth Science and Disaster Prevention, No.321.

Toongoenthong, K. and Maekawa, K. (2005). Multi-mechanical approach to structural performance assessment of corroded RC member in shear, *Journal of Advanced Concrete Technology*, Vol. 3, No. 1, 107-122.

Okamura, H. and Maekawa, K. (1991). *Nonlinear Analysis and Constitutive Models of Reinforced Concrete.* Gihoudou-Shuppan.