PREDICTING POST-PEAK BEHAVIOUR OF HIGH BRIDGE PIER WITH HOLLOW SECTION USING A NEW MODEL FOR SPALLING OF COVER CONCRETE AND BUCKLING OF REINFORCEMENT

Junji MASUKAWA[1], Kumiko SUDA[2] And Koichi MAEKAWA[3]

SUMMARY

The primary objective of this study is to predict post-peak behavior of high bridge piers with hollow section. If hollow piers are subjected to large flexural force, inside concrete is fractured by compression after spalling of concrete cover and buckling of longitudinal reinforcement, and collapse of the whole flange part in compression suddenly occurs. Therefore, in the seismic design of hollow piers, it is important to predict when spalling of concrete cover and buckling of reinforcement occur and to analyze the post-peak behavior of piers. In order to predict spalling and buckling, a new analysis model was proposed. In this model, axial compressive force, secant elastic modulus and curvature of reinforcement are used, and reduction of buckling length, which was induced by decrease of reinforcement stiffness after yielding, can be calculated. Then, this model was installed in the 3 dimensional nonlinear FEM analysis program using layered shell elements. As a result, comparing with past experiments, we successfully predicted not only spalling and buckling but also the post-peak behavior of piers such as moment-curvature response. In addition, we succeeded to predict the post-peak behavior of piers which are subjected to torsional force caused by the horizontal deformation of the girder.

INTRODUCTION

When PC rigid-frame bridges are constructed in the steep mountainous area, piers of these bridges become more than 30 m high in many cases. In Japan, Washimigawa bridge which has a pier of 118 m high has been constructed. Cross sections of these reinforced concrete (RC) high piers frequently become hollow to reduce the influence of self weight of piers during an earthquake. Hollow piers first suffer the spalling of concrete cover outside the compressive flange followed by the buckling of reinforcement as shown in Figure 1. Then the concrete cover spalls and reinforcement buckles inside the section. Finally, internal concrete crushes and the strength deteriorates substantially.

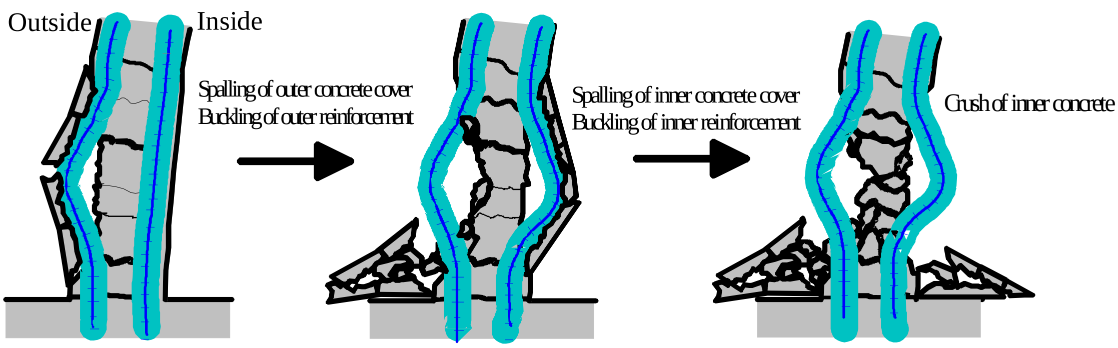


Figure 1: Progress of failure at compressive flanges of a RC member with a hollow section

[1] *Kajima Technical Research Institute, Tokyo, Japan. Email:masukawa@katri.kajima.co.jp*
[2] *Kajima Technical Research Institute, Tokyo, Japan. Email:masukawa@katri.kajima.co.jp*
[3] *Prof., D.Eng. Department of Civil Engineering, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan*

In order to understand the ductility of RC members with a hollow section, the timing of spalling of concrete cover and buckling of reinforcement on the inner and outer sides of the section needs to be predicted accurately. In this paper, models for predicting the timing of concrete cover spalling and reinforcement buckling were proposed. The proposed models have been incorporated into COM3 [Okamura and Maekawa, 1991],[Pallewatta, Irawan and Maekawa, 1996],[Irawan and Maekawa, 1997], the three dimensional finite element analysis program for reinforced concrete, and loading tests of RC hollow pier have been simulated.

ANALYTICAL MODELS FOR SPALLING AND BUCKLING [SUDA, 1999]

Outline of modeling

In order to analyze the spalling of concrete cover and the buckling of reinforcement, concrete cover, hoops and ties were replaced with elasto-plastic spring. Longitudinal reinforcement was replaced with a fixed-end beam subjected to compressive forces. Buckling deformation was approximated by a sine curve. Concrete cover was modeled as spring with tensile stress that decreases with deformation. A point where tensile stress reaches 0 was defined as the point with the critical crack width. The spring constant of hoop k was calculated by building models of hoop and tie with a beam and spring, respectively as shown in Figure 2. Application of the elastic buckling theory to the models shown in Figure 3 enabled calculation of reinforcement buckling length *L* by the following equation.

$$L = 4.4\sqrt[4]{EI/\beta} \tag{1}$$

(E: Apparent stiffness of reinforcement, I: Moment of inertia of reinforcement, β =k/s, s: Spacing of hoops)

Equation (1) shows that the smaller the bending stiffness of the reinforcement and the greater the confining force of the hoop, the shorter the buckling length L becomes. In identifying the apparent stiffness of reinforcement, the effect of softening of plasticized reinforcement was considered. The apparent stiffness was obtained as a gradient of a secant connecting a zero-crossing point where tensile stress changed to compressive stress, and the present point on the reinforcement stress-strain hysteresis curve (see Figure 4). It has been confirmed that the buckling length calculated by this method fairly matches that of past tests [Suda, 1999],[Murayama, Suda, Ichinomiya and Shimbo, 1994].

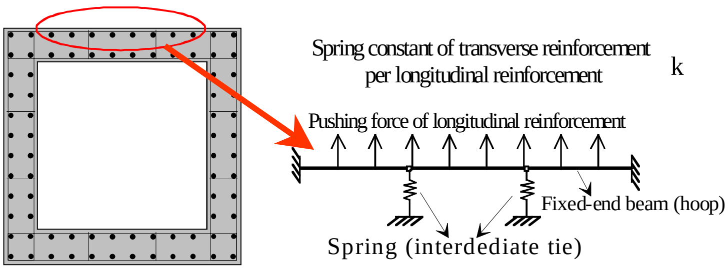


Figure 2: Modeling of transverse reinforcement

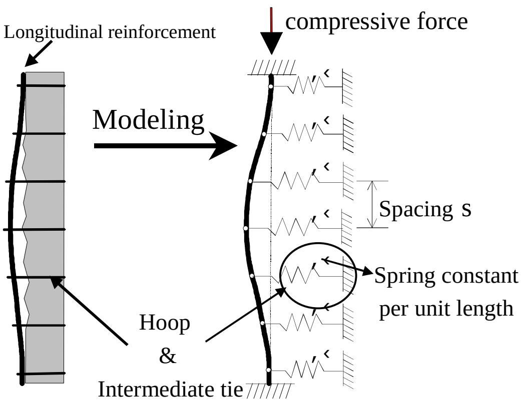


Figure 3: Reinforcement buckling model

Model for predicting the spalling of concrete cover

Spalling of concrete cover occurs as it was pushed outward due to buckling deformation of reinforcement. As shown in Figure 5, slight buckling deformation under compressive force P acting on the reinforcement with a curvature was considered. A buckling stability equation for reinforcement that had concrete cover and initial deformation was derived by Timochenko's energy method. During the derivation of the equation, the width of vertical crack along the reinforcement was assumed to be identical to the additional deflection due to slight buckling deformation. Since the deformation was slight, no confining force of hoop was taken into consideration. As a result of study of stability against buckling, buckling does not occur as long as the confining force of concrete cover applies.

With increases of curvature and compressive force P, slight buckling deformation pushes concrete cover, causing the length *Xu* of the area where concrete cover can not bear the tensile force. The reinforcement buckling length *L*, on the other hand, decreased because plasticization caused the apparent stiffness of reinforcement to decrease (Equation (1)). *L*, therefore, became smaller than *Xu* at a certain time. Then concrete cover no longer bear tensile force for the reinforcement buckling length. That is, the confining force of concrete cover became small enough to be ignored. If the compressive force P at this time is 2.56 times larger than the elastic buckling load in the model in Figure 4, the pier loses its stability against buckling regardless of the initial deformation. Concrete cover is pushed outward by reinforcement and spalls.

Thus concrete cover spalls

when (a) Reinforcement buckling length L is smaller than the length of no-stress section Xu, and

(b) Compressive force P is larger than 2.56 times the elastic buckling load P_a of the model shown in Figure 4.

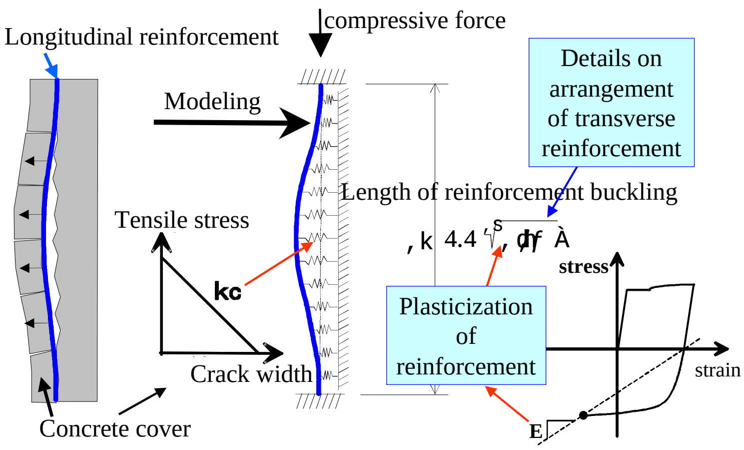


Figure 4: Concrete cover spalling model

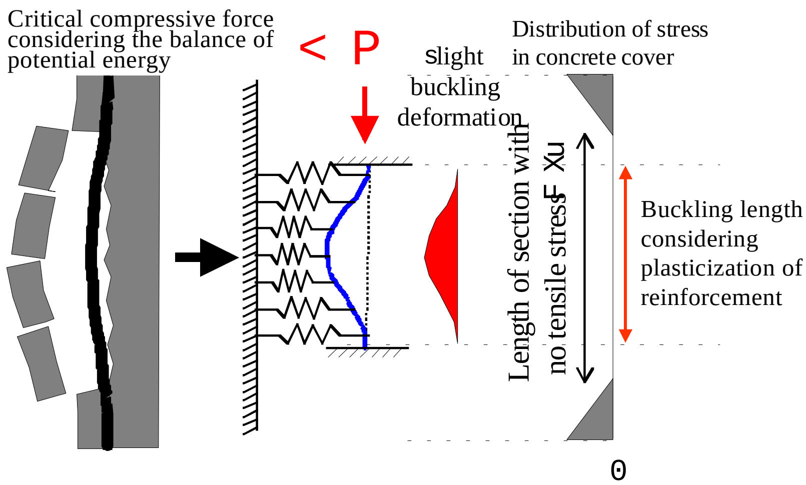


Figure 5: Method of predicting the spalling of concrete cover

Model for predicting the buckling of reinforcement

When the concrete cover spalls, the confining force of the hoop increases rapidly. Thus reinforcement does not immediately buckle substantially. To predict reinforcement buckling with considerable deformation, therefore, the model shown in Figure 3 is used that has no concrete cover and takes the confining force of the hoop into consideration. The buckling of reinforcement is derived from the elastic buckling theory.

Buckling occurs after the spalling of reinforcement
    when (a) Compressive force P is larger than elastic buckling load P_b of the model shown in Figure 3.

The models for predicting the concrete cover spalling and reinforcement buckling described above enable prediction based only on the acting compressive force, stress-strain hysteresis and curvature of longitudinal reinforcement, and on the critical crack width of concrete cover. Therefore the models can be installed into existing analytical software easily.

ANALITICAL STUDY ON THE APPLICABILITY OF THE PROPOSED MODEL

Installation into finite element analysis program

In order to study the applicability of the proposed models for predicting concrete cover spalling and reinforcement buckling results of a loading test with a model specimen were compared with those of simulation analysis. The analysis was carried out by installing the proposed models into COM3 mentioned earlier.

Specimen and modeling

The specimen for analysis [Suda, Amano, Masukawa and Ichinomiya, 1997] is outlined in Figure 6. Cross section is hollow from the bottom to a height of 120cm of the column. For loading, axial force (axial stress: 3.53 N/mm^2), bending moment, torsional moment and shear force were applied at the top of the columnar specimen. Cyclic forces were applied repeatedly at a shear span ratio of 5. A torsional moment equivalent to 15% of bending moment at the bottom was applied until the stress of the tensile reinforcement reached 90% of the yield strength (which was equivalent to the allowable stress during an earthquake). After this stage, displacement-control loading was carried out so that the ratio could be kept constant between the average curvature and the torsional rotation angle at the 90-cm height from the column bottom when the tensile reinforcement reached 90% of the yield strength. A diagram of mesh is shown in Figure 7, and the properties of materials used in the analysis are listed in Table 1.

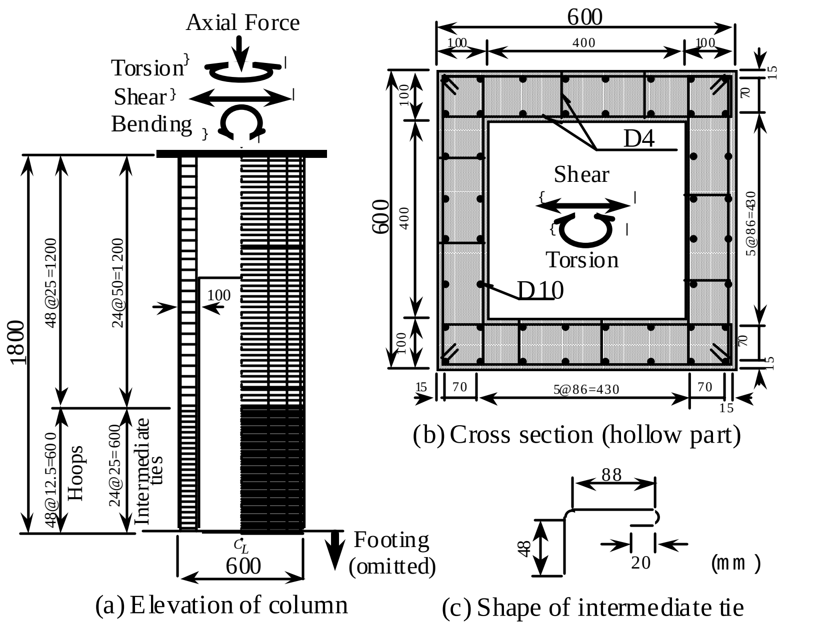
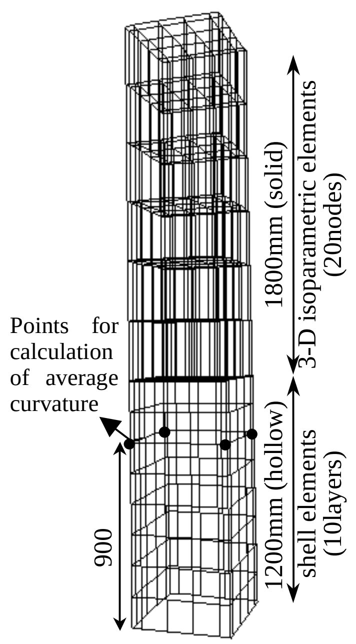


Figure 6: Outline of a specimen [Suda, et al., 1997]



Firure 7: Diagram of mesh

Only the column was modeled. The hollow section was modelled with RC layered shell elements [Irawan and Maekawa, 1997]. An element was 12.5 cm wide and 15 cm high as shown in Table 1. The solid section was modelled with 3-D isoparametric elements. The solid portion was made 120 cm longer than the specimen so that the distribution of bending moments and shear forces at the base of the column might be the same as for the specimen for analysis to which loads were applied at a shear span ratio of 5. Since D10 reinforcement with a relatively smaller diameter than that of the section was used as the longitudinal reinforcement of the specimen, the effect of pullout of longitudinal reinforcement from the footing was ignored in the analysis.

Table 1: Material Properties used in analysis

Compressive strength of concrete	86.0 N/mm^2
Tensile strength of concrete	3.24 N/mm^2
Young's modulus	31300 N/mm^2
Poisson's ratio	0.2
Yield strength of longitudinal reinforcement	866 N/mm^2
Longitudinal reinforcement ratio	1.712 %
Yield strength of hoop	284 N/mm^2
Hoop ratio (1D at the bottom)	2.01 %
Hoop ratio (other part)	1.005 %
Thickness of shell elements	100 mm
Number of layers	10
Largeness of shell element	125mm x 150mm

Figure 8 is a diagram of a RC layered shell element. Longitudinal reinforcement was applied in the specimen with a hollow section either on the outer and inner side of the section. Inner and outer layers of concrete cover were also set into shell elements. Prediction of concrete cover spalling and reinforcement buckling were performed at each Gauss point (four per layer) on a layer of reinforcement. When concrete cover spalling or reinforcement buckling was detected, the following actions were taken. The authors have already developed a post-buckling reinforcement hysteresis model [Murayama, Suda, Ichinomiya and Shimbo, 1994]. A simplified model was, however, used in this analysis.

(i)In the case of concrete cover spalling:
Stress of concrete cover layers was reduced to 0.

(ii)In the case of reinforcement buckling:
Stress of concrete layers outside the reinforcement layer corresponding to the Gauss point was reduced to 0.
In case the stress of the reinforcement in the reinforcement layer was compressive, it was reduced to 0.
In case the stress of the reinforcement in the reinforcement layer was tensile, it was reduced to 80%.

At corners, hoops were arranged double. Therefore, no reinforcement buckling was assumed but only concrete cover spalling was assumed. For core concrete, concrete compressive strength was evaluated by a method developed by Pallewatta et al. [Pallewatta, Irawan and Maekawa, 1996] considering confining effect of transverse reinforcement.

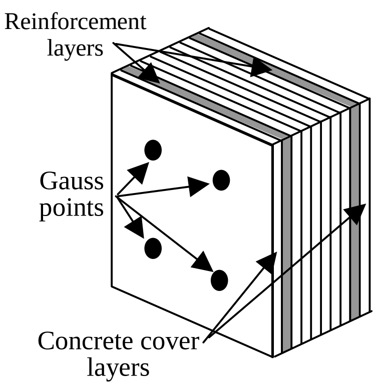


Figure 8: Layers of shell element

As shown in Figure 9, bending and torsional loads were aplied by providing compulsory displacement at four points in corners at the top of the column so that the ratio between the curvature and torsional rotation angle might be the same as in the test. Loading was repeated three times with the same displacement in the test, but repeated only once in the analysis.

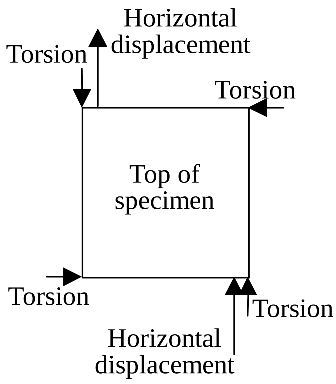


Figure 9: Loading in analysis

Results of analysis

Figure 10 shows a relationship between the bending moment at the bottom and the average curvature in a 90-cm section at the bottom of column. Figure 11 shows a relationship between the torsional moment and the torsional rotation angle in a 90-cm section at the bottom of the column. Both figures compare results of experiment and analysis.

In experiment, under the condition of $4\varphi_y$ through $5\varphi_y$ (φ_y =10x10^{-6}/mm), spalling of concrete at corners of the base of the column progressed. In the third cycle of $5\varphi_y$ through $7\varphi_y$, reinforcement buckled and the ultimate state was reached as in the case of ordinary bending failure.

Figure 10 shows that the initial gradient until the yielding load due to bending was slightly larger in the analysis than in the test. With respect to the maximum strength and the timing of strength deterioration, the test results agreed to the analytical results with a great accuracy. The analysis considered no effect of pullout of reinforcement from the footing, but the accuracy of analysis was hardly affected.

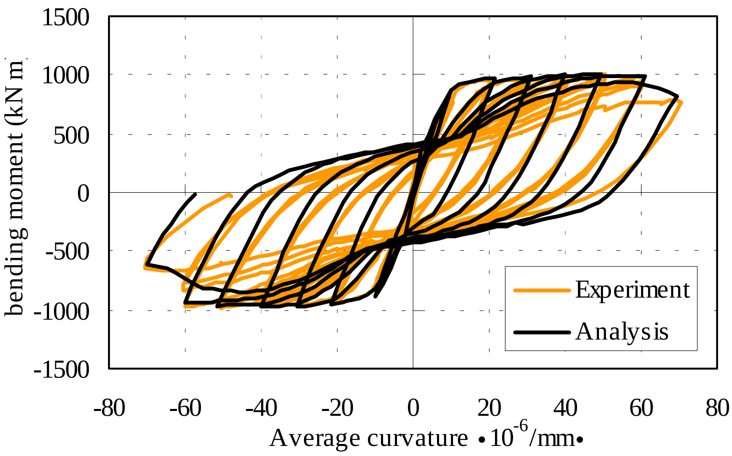


Figure 10: Relationship between bending moment and average curvature

In the relationship between the torsional moment and the torsional rotation angle shown in Figure 11, torsional stiffness after the spalling of concrete cover is evaluated large. One reason may be that the proposed models for concrete cover spalling and reinforcement buckling consider only the case where compressive forces act on reinforcement. In order to identify the torsional strength and deformation behavior of RC members, the mechanism of concrete cover spalling due to torsion needs to be considered. However sufficient ductility is provided under combined sectional force expected on high bridge piers because adequate reinforcement against torsion can prevent torsional failure.

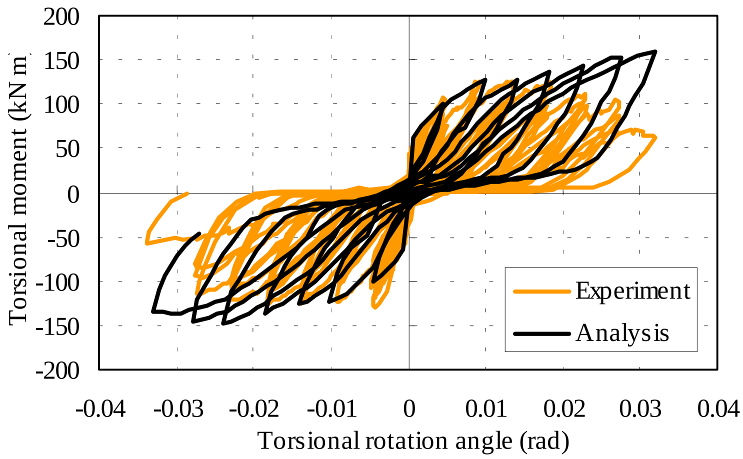
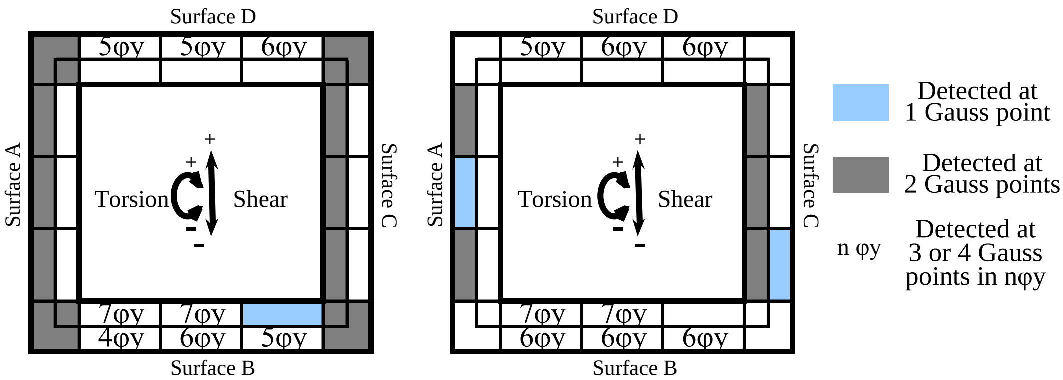


Figure 11: Relationship between torsional moment and torsional rotation angle



(a) Spalling of concrete **(a) Buckling of reinforcement**

Figure 12: Prediction of timing of spalling and buckling at the bottom of the column

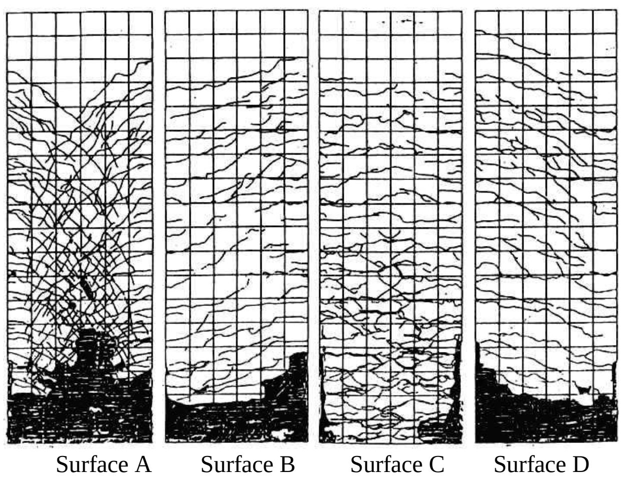


Figure 13: Cracking and spalling of the specimen after loading (10 cm per box)

As shown in Figure 10, therefore, ductility of RC high bridge piers with a hollow section can be evaluated fairly accurately by incorporating the proposed models into analysis even when no spalling behavior of concrete cover due to torsion is considered.

Figure 12 shows results of prediction of timing of concrete cover spalling and reinforcement buckling with respect to elements at the bottom of the column. As described earlier, prediction was made for each of the four Gauss points in the two reinforcement layers on the inner and outer side of each element. The numbers of Gauss points indicates the numbers for which spalling or buckling was detected. Larger numbers, therefore, represent further progress of spalling or buckling in the particular element. Figure 12 indicates that in addition to the spalling of concrete cover on the outer side of surfaces B and D of the section at the flange, concrete cover spalled almost throughout the outer side of surface A where the shear stress due to torsional moment applied in the same direction as shear force. The results agree to the ultimate cracking shown in the test represented in Figure 13.

Thus, simulation of the concentration of failure under the combined sectional force was considered possible by the proposed models.

CONCLUSIONS

For the evaluation of ductility of RC hollow piers, new models have been proposed for predicting the timing of concrete cover spalling and reinforcement buckling. They take into consideration the difference in confining force according to the arrangement of transverse reinforcement, variations in bending stiffness of reinforcement with plasticization, initial deformation according to curvature of the member, and the tensile and confining characteristics of concrete cover. In order to evaluate the applicability of the proposed models, a model test for high piers under combined sectional force was simulated. As a result, it was confirmed that the bending ductility of RC bridge piers with a hollow section which experienced bending failure could be evaluated accurately.

REFERENCES

Irawan, P. and Maekawa, K. (1997) “Path-dependent Nonlinear Analysis of RC Shells Subjected to Combined In-plane Membrane and Out-of-plane Flexural Actions, *Concrete Library of JSCE*, No.30, pp.221-238.

Murayama, Y., Suda, K., Ichinomiya, T. and Shimbo, H. (1994) “ A Buckling Model of Longitudinal Reinforcing Bars under Reversed Cyclic Load”, *Annual Report of Kajima Technical Research Institute*, Vol.42, pp.93-98.

Okamura, H. and Maekawa, K. (1991), *Nonlinear Analysis and Constitutive Models of Reinforced Concrete*, Gihodo, Tokyo.

Pallewatta, T.M., Irawan, P. and Maekawa, K. (1996) “Confinement Effectiveness of Lateral Reinforcement Arrangements in Core Concrete, *Concrete Library of JSCE*, No.27, pp.221-247.

Suda, K. (1999) “ Study on the Seismic Performance of RC High Piers with Hollow Section”, Doctoral Thesis, The University of Tokyo, Tokyo.

Suda, K., Amano, R., Masukawa, J. and Ichinomiya, T. (1997), “Effects of Torsion on Ductility of High-piers ”,*Proc. of JCI*, Vol.19, No.2, pp.789-794.