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Nonlinear Analysis on Seismic Behavior of Reinforced Concrete Members using Laminated Shell Elements

Seiji Nagata[1], Toyofumi Matsuo[2] and Yasumune Shigemitsu[3]

[1] Research Scientist, Central Research Institute of Electric Power Industry, Chiba-ken, Japan (n-seiji@criepi.denken.or.jp)
[2] Senior Research Scientist, Central I Research Institute of Electric Power Industry, Chiba-ken, Japan
[3] Group Manager, Kansai Electric Power, Co., Inc., Osaka-fu, Japan

ABSTRACT

A series of numerical simulations on the past static loading experiments of reinforced concrete specimens are presented. These analyses are carried out to verify applicability of the laminated shell element as a simpler three-dimensional nonlinear finite element method for seismic performance evaluation. In particular, the analyses considering material nonlinearity of concrete and reinforcing bars in layers of the laminated shells are performed for reinforced concrete slab, box culvert, and large-scale column specimens. Based on comparison with the test results, good predictions are obtained regarding hysteretic load and displacement performance of the reinforced concrete specimens under various loading conditions. These results indicate that the laminated shell element is useful for evaluating the nonlinear behaver of structures subjected to in-plane and out-plane loads.

INTRODUCTION

In the current seismic design procedures of the critical civil engineering structures in Japanese nuclear power plants, a three-dimensional analysis method of reinforced concrete (hereinafter RC) structure has been incorporated to provide more realistic and rational performance verification (Maekawa et al. 2003, and Japan Society of Civil Engineering 2018). For the underground structures such as a box culvert for seawater intake channels and piping ducts, nonlinear solid elements are generally utilized in a three-dimensional nonlinear analysis if complex behavior of structural systems should be concerned. However, it takes a lot of time and effort in modeling, calculation, and post-processing procedures especially when whole structural system and surrounding soils are needed to be included. As a simpler three-dimensional method, a laminated shell element is available for modeling shear walls and slabs of buildings in which the in-plane shear deformation is relatively predominant during the event of an earthquake. On the other hand, there are relatively few analysis cases applied for the RC underground structures which subjected to the in-plane as well as the out-plane loadings.

Based on the background described above, numerical simulations for the experimental behavior with various geometry and loading conditions are performed. In the analyses, the laminated shell elements, including a set of constitutive models based on one-directional stress-strain field of cracked concrete as well as reinforcing bars, are adopted. Firstly, numerical verifications using RC slab and RC box culvert specimens which subjected to mainly out-of-plane cyclic deformations (Irawan and Maekawa 2003) are carried out. In addition, analytical simulations for full-scale RC members without and with seismically retrofitted by the post-installed shear reinforcing bars subjected to horizontal monotonic loading (Komatsu et al. 2021) are carried out, and the in-plane and the out-plane nonlinear force-displacement performance of the laminated shell elements are clarified.

ANALYTICAL METHOD

A series of numerical analyses simulating past loading tests are conducted by using an analysis software TDAP III ver.3.12 (Ark Information Systems 2020). The laminated shell element used in this analysis is an element that are divided by layers in the out-of-plane direction. In this element, the constitutive rules of concrete and reinforcing bars applied for each layer of the two orthogonal in-plane directions. The main feature of this elements is that it is possible to consider the non-linearity of axial force, bending moment and shear force in the in-plane direction. On the other hand, in the out-of-plane direction, only the nonlinearity of axial force and bending moment can be considered (the nonlinearity of the out-of-plane shear deformation cannot be included). To consider the linear shear deformation in the out-of-plane of a shell element, Mindlin-Reissner plate theory is applied.

As for the constitutive rule of concrete, the modified Ahmad equation (Ahmad et al. 1982, and Naganuma et al. 2004) and Izumo equation (Izumo et al. 1989) are applied to the compressive and tensile properties of concrete, respectively. Formulations developed by Naganuma is utilized for the shear transfer functions and compressive strength reduction characteristics after cracking (Naganuma 1991). In the tensile model after a crack occurs, the tensile hardening is considered for RC elements, due to the effect of the bonding between the reinforcing bar and concrete, while the tensile softening model is applied for plain concrete elements. To represent the nonlinear stress-strain characteristics of the reinforcing bar, the constitutive law considering the Bauschinger effect is applied (Menegotto and Pinto 1973).

VERIFICATIONS BASED ON SLABS AND A BOX CULVERT

Numerical verifications based on the idealization using TDAP III described above for the laminated shell element based on RC slab specimens and a RC box culvert specimen which subjected to mainly out-of-plane cyclic loadings (Irawan and Maekawa 1997) are presented below.

RC slab specimens

Figure 1 and Figure 2 illustrate RC slab specimens and the analysis idealization, respectively. The material properties and reinforcement ratios of the specimens are summarized in Table 1. Two slabs named as specimen IS-1 and IS-2 with different arrangement of main reinforcing bars are used to clarify the predicting capability of hysteretic behavior of the RC members. The specimen is a square RC member with a side length of 1,800 mm and a thickness of 100 mm. In the IS-1 specimen, reinforcement ratios in x and y directions are equal, while in the specimen IS-2 reinforcement ratio in y direction is half of that in x direction. In both RC specimens, reinforcing bars with 10 mm in diameter are arranged in two layers (top and bottom) in each horizontal direction.

As the experimental condition, these slabs were simply supported on four sides (1,400 mm by 1,400 mm), and the out-of-plane cyclic load was applied at the center of the slab through loading plate. On the other hand, in this analysis, a half model with 6 by 3 element meshing was developed as shown in Figure 2, considering the symmetry of the slab in y direction. The concrete part outside the supports was eliminated in the analytical model because its effect may be negligible. A laminated shell element was divided by ten layers for the integration through the element thickness. Figure 3 compares load-deflection relationships of slabs between analyses and experiments. According to these hystereses, the analytical models using the laminated shell elements well simulate the nonlinear envelope curves and the cyclic loops of the slab specimens due to cracking of concrete as well as yielding of the reinforcing bars developed in these RC slab specimens.

Table 1: Main properties of RC slabs used for the analytical verification.

Specimen	Concrete	Main Reinforcing bar		
	Compressive strength (N/mm^2)	Tensile yielding stress (N/mm^2)	Ratio in x direction (%)	Ratio in y direction (%)
IS-1	37.0	380	0.78	0.78
IS-2	37.0	380	0.78	0.39

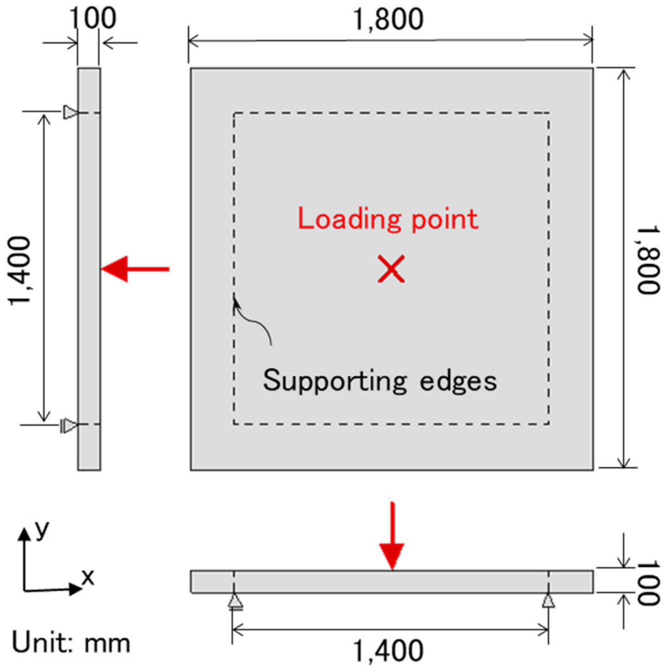


Figure 1. Configuration of RC slab.

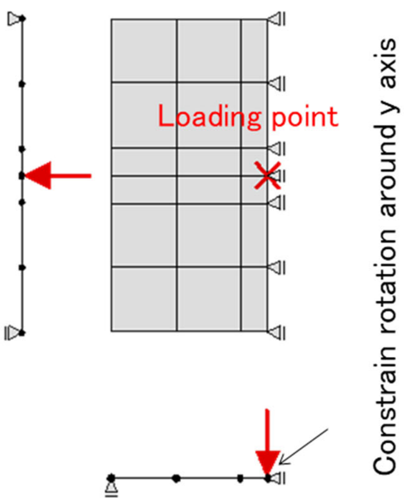
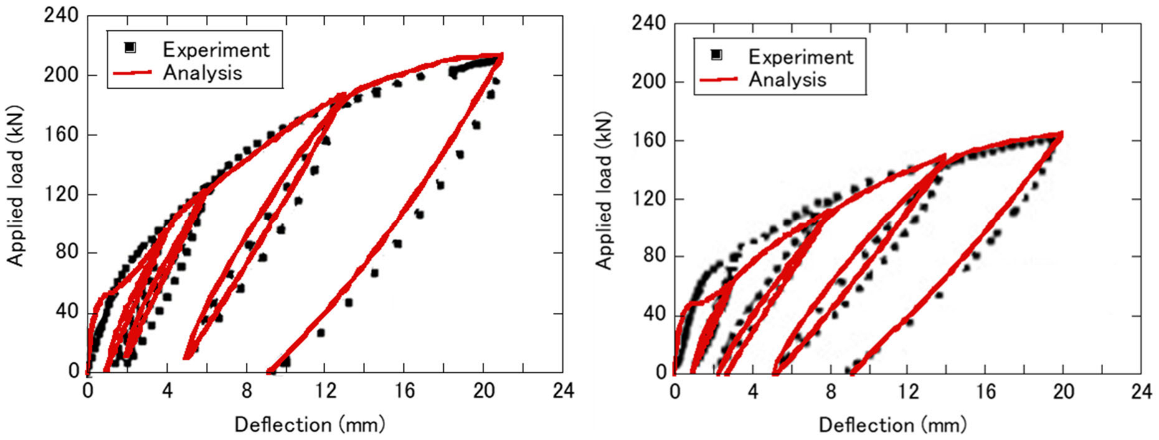


Figure 2. Modeling for RC slab.



(a) Specimen IS-1 (Isotropic slab) (b) Specimen IS-2 (Anisotropic slab)

Figure 3. Correlation of force-displacement relationships for RC slabs.

RC box culvert specimen

The RC box culvert specimen and its modeling are depicted in Figure 4 and Figure 5 respectively. Table 2 summarizes material properties and reinforcement ratios of the specimen. The external dimensions of the box culvert are 2,360 mm in height, 2,320 mm in width, and 1,480 mm in depth. The thicknesses of the side walls and the slabs (both top and bottom) are 160 mm and 180 mm, respectively. In each member, reinforcing bars with 16 mm in a diameter is arranged in two layers at 150 mm intervals as the main reinforcement (vertical reinforcements), and bars with a diameter of 10 mm is provided in two layers at 400 mm intervals as the distributing reinforcements (horizontal reinforcements). At the corners there are four haunches of 200 by 200 mm in size.

During the experiment, the box culvert was simply supported on the bottom slab, whereas the specimen was vertically loaded with cyclic excursion at the top slab as shown in Figure 4. Under this kind of loading condition, the top slab would exhibit biaxial bending moments and torsion, and the bottom slab was subjected to combination of in-plane load, bending moment, and torsion. In the analysis idealization, only a half of box culvert specimen was required to be modeled due to the symmetry along the width direction. For the top and the bottom slabs, 5 by 4 shell elements were applied, while 10 by 4 shell elements were adopted for both side wall, ignoring the presence of the haunches. Each shell element was divided into seven layers for the integration through the thickness.

Figure 6 presents comparison of the experimental and the analytical results in terms of applied load and deflection relationship at loading point of the top slab. According to these hystereses, general trend of the load-deflection relationship including the nonlinear envelope curves and the cyclic loops are well predicted by using the laminated shell elements.

Table 2: Main properties of RC box culvert used for the analytical verification.

Member	Concrete	Main Reinforcing bar		
	Compressive strength (N/mm^2)	Tensile yielding stress (N/mm^2)	Ratio in cross-sectional direction (%)	Ratio in longitudinal direction (%)
Wall	50.0	400	1.87	0.27
Slab	50.0	400	1.66	0.24

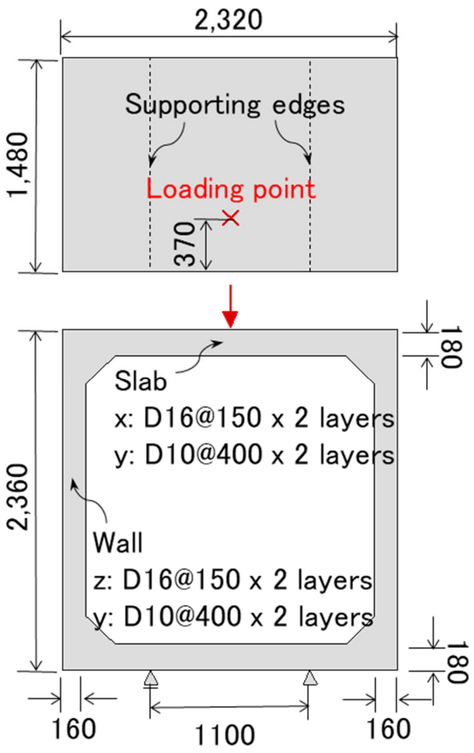


Figure 4. RC box culvert specimen.

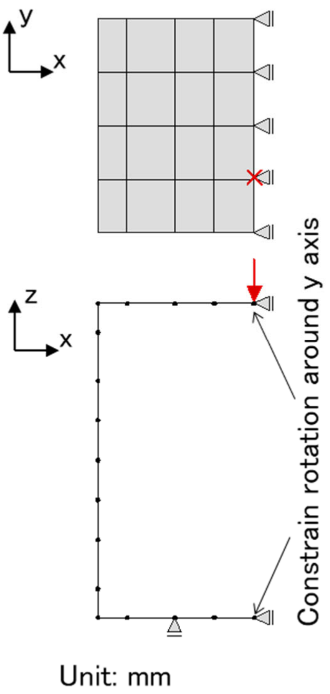


Figure 5. Modeling for RC box culvert.

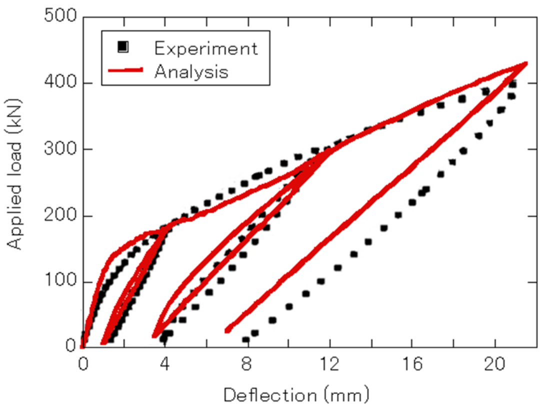


Figure 6. Correlation of force-displacement relationships for RC box culvert.

VERIFICATIONS BASED ON LARGE-SCALE RC MEMBERS

The full-scale RC members called as specimen N-1 and P-1 are presented in Table 3 and Figure 7 as target structures for the analysis. Actually, the original research target was RC wall which consist of box culverts for seawater intake channels and piping ducts at an electric power plant, but in this experiment, columns with a square section (thickness of 1.1 m) were prepared, considering the load capacity and restrictions of the experimental devices. Both specimens were firstly constructed such that they exhibit shear failure, and after that the specimen P-1 was seismically retrofitted by using the post-installed reinforcements. As a result, the specimen N-1 and P-1 exhibit shear failure and flexural failure, respectively.

For the specimens, main reinforcing bars with a diameter of 32 mm were placed at intervals of 150 mm, and shear reinforcements of 13 mm in a diameter were arranged with intervals of 300 mm. The cover thickness of concrete between the outermost edge and the center of the main reinforcing bar is 100 mm. The height from the member base to the loading point is 2.6 m, and the shear span ratio is 2.6. In the specimen P-1, after drilling holes from one side, post-installed shear reinforcing bars with diameter of 16 mm was inserted with intervals of 300 mm and filled with mortar. The concrete compressive strengths of specimen N-1 and P-1 according to the material test are 36.9 N/mm^2 and 36.2 N/mm^2, respectively, as shown in Table 3. The yield strengths and ratio of the main reinforcing bar is 508 N/mm^2 and 0.51 %, respectively.

Table 3: Main properties of full-scale RC members used for the analytical verification.

Specimen	Concrete	Main Reinforcing bar	
	Compressive Strength (N/mm^2)	Tensile yielding stress (N/mm^2)	Ratio in longitudinal direction (%)
N-1	36.9	508	0.51%
P-1	36.2	508	0.51%

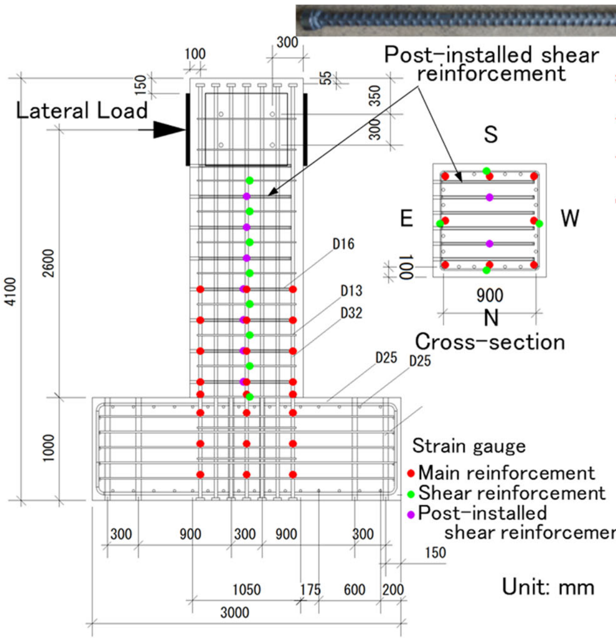


Figure 7. Full-scale RC member (P-1).

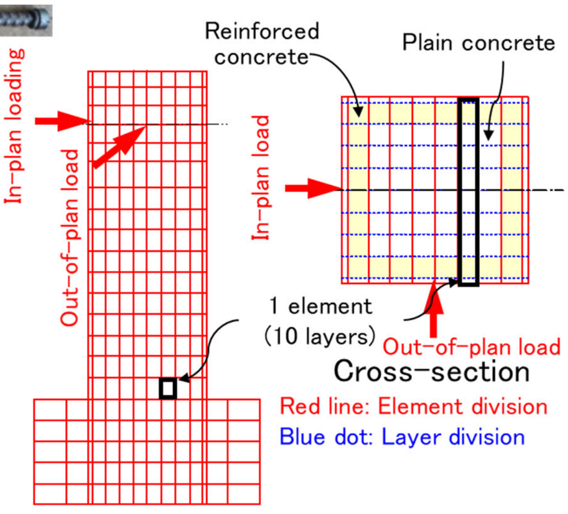
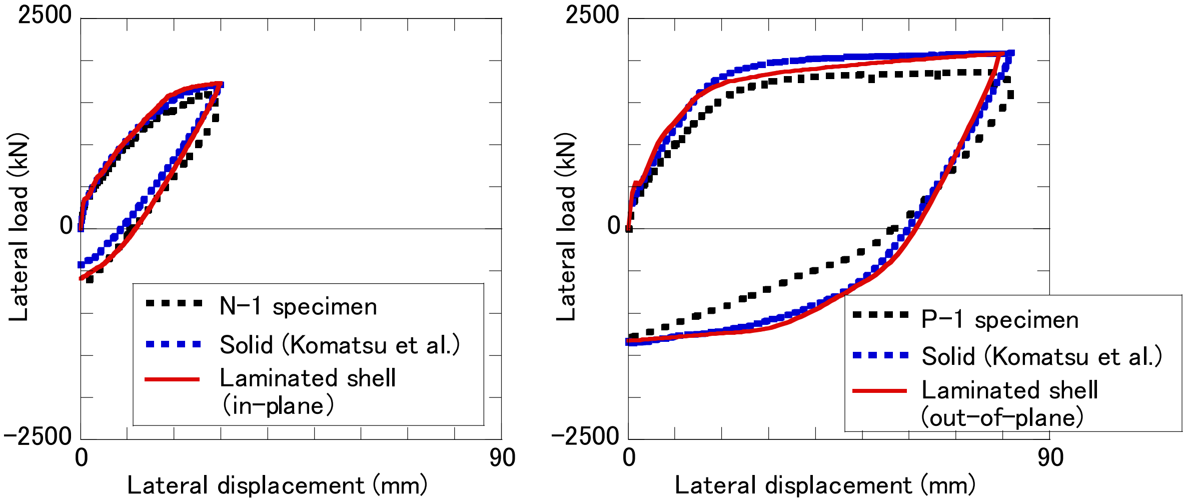


Figure 8. Modeling for Full-scale RC members.

Even though the original purpose of the experiment is to verify the effectiveness of seismic retrofitting and to clarify the structural performance under bilateral loading hystereses, in the present paper only unilateral monotonic loading conducted as the initial loading procedure is set to analysis target to obtain basic knowledge for the laminated shell elements. Under the monotonic loading test for the specimen N-1, diagonal cracks with a maximum crack width of 5 mm occurred, which caused significant deterioration in the horizontal strength of the RC specimen. Meanwhile, in the specimen P-1, horizontal cracks were distributed at the relatively lower part of the RC specimen, and diagonal cracks also occurred but the remarkable progress was restrained by the post-installed shear reinforcements.

In this research, modeling and reproducibility are discussed by focusing on the fact that the nonlinearity of axial force, bending moment, and shear force can be considered the in-plane direction of the laminated shell element, whereas the nonlinear shear behavior cannot be simulated in the out-of-plane direction. Figure 8 presents element and layer divisions for the full-scale RC member. In this idealization, the normal and post-installed shear reinforcing bars is not modeled directly, and the in-plane and out-of-plane directions of the laminated shell element model are assumed to correspond to specimens N-1 and P-1 (without and with the post-installed shear reinforcements), respectively. This division of elements and layers and the material property (see Table 3) are matched with the previous modeling using solid element (Komatsu et al. 2021). To properly consider the bonding effect between the reinforcing bar and concrete, the cross section of the column was divided into RC element with the tension hardening model and plane concrete element with the tension softening model, respectively. In the analyses, in-plane and out-of-plane loadings are applied individually to the laminated shell model to simulate the experimental results when the specimen N-1 and P-1 are monotonically loaded, respectively.



(a) Specimen N-1 (b) Specimen P-1

Figure 9. Correlation of force-displacement relationships for full-scale RC members.

Figure 9 presents the horizontal load and displacement relationship of the laminated shell element model developed due to in-plane and out-of-plane loadings, comparing them with the experimental results of the specimens N-1 and P-1, respectively. The past analysis results by the solid element using the program COM3 (Komatsu et al. 2021) are also shown here. The behavior of the specimens N-1 and P-1 up to the maximum load capacity under the monotonic loading can be well predicted by imposing the in-plane and the out-of-plane loadings to the laminated shell element model, respectively. These accuracies seem to be almost the same as those of the solid elements.

SUMMARY

To contribute to rationalization and practical application of the seismic performance verification using three-dimensional nonlinear analysis for critical civil engineering structures at Japanese nuclear power plants, a series of analyses predictions of past experiments using laminated shell elements were successfully performed. As a simpler three-dimensional analytical method that can reduce the number of nodal points for integration and the calculation effort compared with the solid elements, applicability of laminated shell element is validated through the simulations. In comparison with the test results, good predictions are obtained regarding load capacities and hysteretic loops of RC slabs, box culvert, large-scale columns respectively which subjected to the in-plane and the out-of-plane loads. However, it is required to continue analytical work which consider various cross-sectional shapes, effect of combination of the in-plane and the out-of-plane loading hystereses, and effects of the surrounding soils.

ACKNOWLEDGEMENTS

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