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Nonlinear Analysis of Prestressed Knee-Joint under Seismic Loads

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ABSTRACT

Given that there is a lack of nonlinear analysis of knee-joint type elements, in this study, sophisticated nonlinear analysis is conducted. Using OpenSees, reinforced concrete knee joint models with various design conditions are analyzed under the lateral seismic loads. In order to simulate the backbone and strength deterioration, Ibarra-Medina-Krawinkler (IMK) model is used in nonlinear analysis. Verification of the modeling is carried out by comparison with previous data from a variety of RC knee-joint experimental models.

1. INTRODUCTION

In 2002, Joint ACI-ASCE Committee 352 reported the ACI 352R-02, the recommendations for design of beam-column connections of reinforced concrete (Joint ACI-ASCE Committee 352 2002). However, the recommendations have deficient information about post-tensioned knee joints. In reality, the recommendations pointed out that a post-tensioned joint is still open to be researched in its appendix. In addition, nonlinear analysis of post-tensioned knee joint has not been performed sufficiently to date. Thus, in this study, nonlinear analysis for various post-tensioned knee joints is carried out using the OpenSees. Comparing with the experimental data, the credibility of the nonlinear analytical model is checked.

2. EXPERIMENTAL MODEL

For verification of the nonlinear analysis, previous experimental specimens were inspected first. For this study, three different knee-joint specimens (K-PT-N-1, 2, 3) were used for nonlinear analysis (Kwon 2016). Each specimen had the same cross

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section area but different reinforcement. All the specimens were post-tensioned by 4 tendons. In order to improve constructability, headed bars were used for reinforcement of the joint part. The key parameters of each specimen are summarized in Table 1.

Table 1 Details of knee joint specimens

Specimen	Beam size (mm)	Column size (mm)	f'_c (MPa)	f_y (MPa)	M_{pr} (kN·m)
K-PT-N-1	400×560	500×750	35	400	383
K-PT-N-2	400×560	500×750	35	400	509
K-PT-N-3	400×560	500×750	35	400	635

A test specimen is shown in Fig. 1 (Kwon 2016). The experiment was carried out under displacement control.

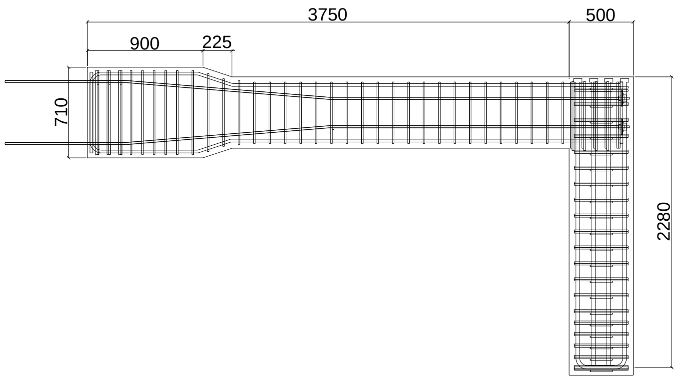

Fig. 1 Section of experimental specimen K-PT-N-1 (Unit: mm) (Kwon 2016)

3. NONLINEAR ANALYSIS

In order to generate moment-rotation backbone relationship for nonlinear analysis, the modified Iberra-Medina-Krawinkler deterioration model with pinched hysteric response (IMK pinching model) is used. This model is developed by Lignos and Krawinkler by modifying the original Iberra-Medina-Krawinkler Model for asymmetric backbone curve (Fig. 2) (Lignos and Krawinkler 2011; Iberra et al. 2011; Lignos and Krawinkler 2013). The parameters for the curve in Fig. 2 are calculated from specifications of specimens (Table 2). Residual moment, post-capping rotation capacity and ultimate rotation are determined from experiment.

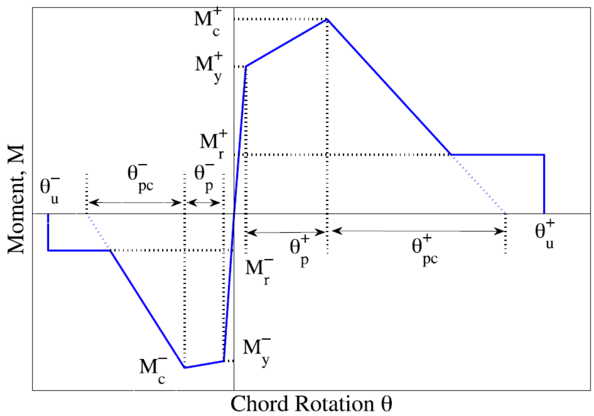

Fig. 2 Backbone curve of IMK pinching model (Lignos and Krawinkler 2013)

Table 2 Basic Parameters for Backbone Curve

	Definition	**Equations**
E [a]	Initial rotational stiffness	$= \infty$ (in code, 2×10^{12} is used)
M_c^+	Positive capping moment	$= M_{pr}$ [a]
M_c^-	Negative capping moment	$= 0.8M_{pr}$ [b]
$M_y^\pm$	Yielding moment	$= 0.8M_c^\pm$ [b]
$M_r^\pm$	Residual moment	$= 0.2M_c^\pm$ 0(ASCE/SEI 41 2007)
$\theta_p^\pm$	Pre-capping rotation capacity	$= (\phi_u - \phi_y) \times l_p$, where $l_p = 0.08L + 0.022d_bf_y$ (Pauley and Priestley 1992) [c]
$\theta_{pc}^\pm$	Post-capping rotation capacity	$= \pm0.3$ [d]
$\theta_u^\pm$	Ultimate rotation	$= \pm1$ [d]

a. M_{pr} is shown in Table 1
b. The equations are assumed in this study.
c. ϕ_u = ultimate curvature of beam; ϕ_y = yield curvature of beam; l_p = plastic hinge length of beam; L = beam center-to-center span length; d_b = bar diameter; f_y = specified yield strength of steel.
d. The values are determined from the experimental data.

From these parameters, the backbone curves are plotted (see Fig. 3).

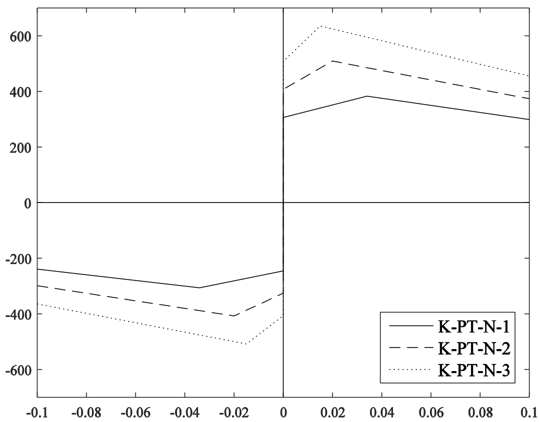

Fig. 3 Backbone curve for nonlinear anlaysis

In addition, the IMK Pinching Model has functional parameters for calibrating backbone curves from experimental data through the following two equations (Lignos and Krawinkler 2011):

$$M_i = (1-\beta_i)M_{i-1} \quad (1)$$

$$K_i = (1-\beta_i)K_{i-1} \quad (2)$$

where M_i is the strength value in current excursion; $M_{i\text{-}1}$ is the strength value in previous excursion; K_i is the stiffness value in current excursion; $K_{i\text{-}1}$ is the stiffness value in previous excursion and β_i is the deterioration parameter, which is determined by:

$$\beta_i = \left(E_i \div \left(E_t - \sum_{j=1}^{i-1} E_j\right)\right)^c \quad (3)$$

where E_i is the dissipated energy in current excursion; E_t is the energy dissipation capacity; ΣE_j is the total dissipated energy in all previous excursions and c is the exponent for controlling the deterioration rate (Iberra and Krawinkler 2005). The energy dissipation capacity is calculated by the following equations:

$$E_t = \lambda \times \theta_p \times M_y \quad (4)$$

$$\Lambda = \lambda \times \theta_p \quad (5)$$

where Λ is the reference cumulative rotation capacity; λ is the dimensionless value for simulating strength deterioration rate; θ_p is the pre-capping plastic rotation and M_y is the yielding moment.

When the IMK deterioration model is used, parameters Λ and c are necessary. In the experimental data of the post-tensioned knee-joint, K-PT-N-1, the parameters Λ and c are determined through the iterated calculation process that finds the closest trend. By continuing to compare calculated beta values from the energy dissipation of K-PT-N-1 and actual beta values from capping moment values, the parameters Λ and c are defined as 1.34 and 1.2, respectively (see Fig. 4).

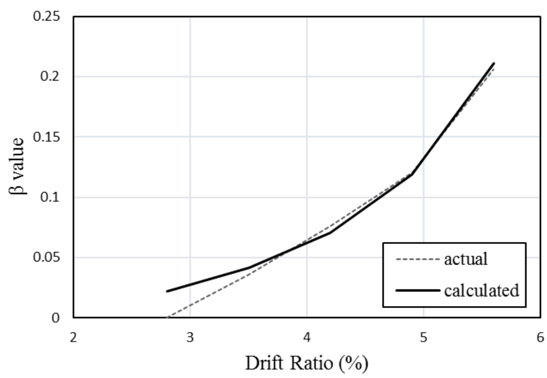

Fig. 4 K-PT-N-1's β value comparison with Λ = 1.34 and c = 1.2

Through such a calculation process, the nonlinear analysis parameters of each experimental specimen are defined as indicated in Table 3.

Table 3 Parameters for Strength Deterioration

	λ	c	θ_p [a]	Λ
K-PT-N-1	39.5	1.2	0.034	1.3448
K-PT-N-2	65.0	1.2	0.020	1.3302
K-PT-N-3	43.0	1.2	0.015	0.6285

a. θ_p is the pre-capping rotation capacity of positive drift ratio direction.

For the beam and column elements, Elastic Beam-Column element and Displacement-Based Beam-Column element are used, respectively. The key parameters are calculated from the section and material properties. According to the original experimental model, the analytical model has a hinge as a boundary condition for the column end, and the displacement of the beam is controlled to the specific axis; the nodes on the beam element are controlled not to move along the Y and Z axis. Under these conditions, nonlinear analysis is performed. The analysis results are processed and organized using Matlab.

4. RESULT COMPARISON

Using the parameters defined in Table 3, nonlinear analysis using the IMK pinching model is carried out. Fig. 5 to 7 show the comparison of experimental data with analysis results.

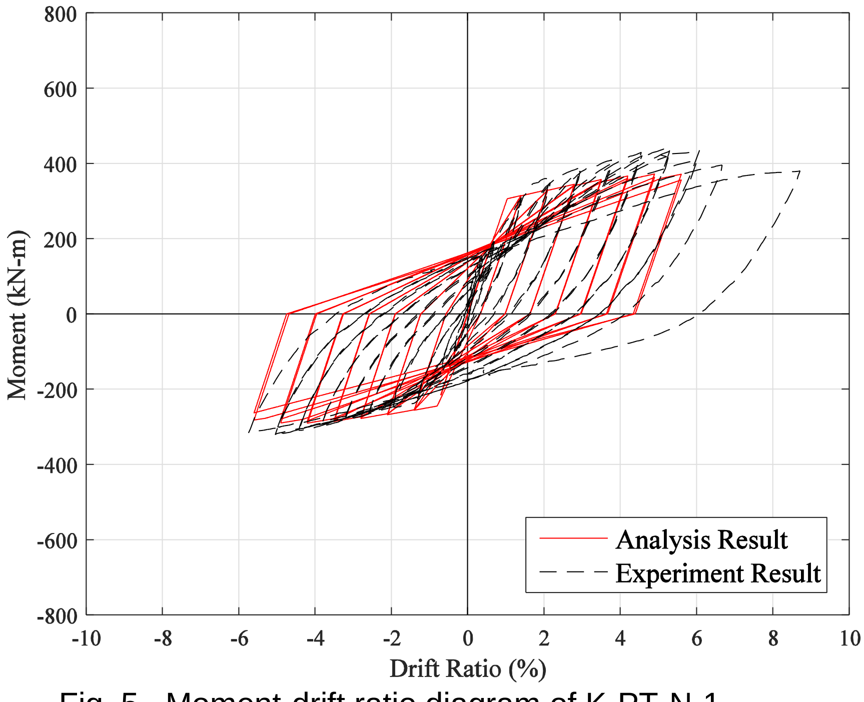

Fig. 5 Moment-drift ratio diagram of K-PT-N-1

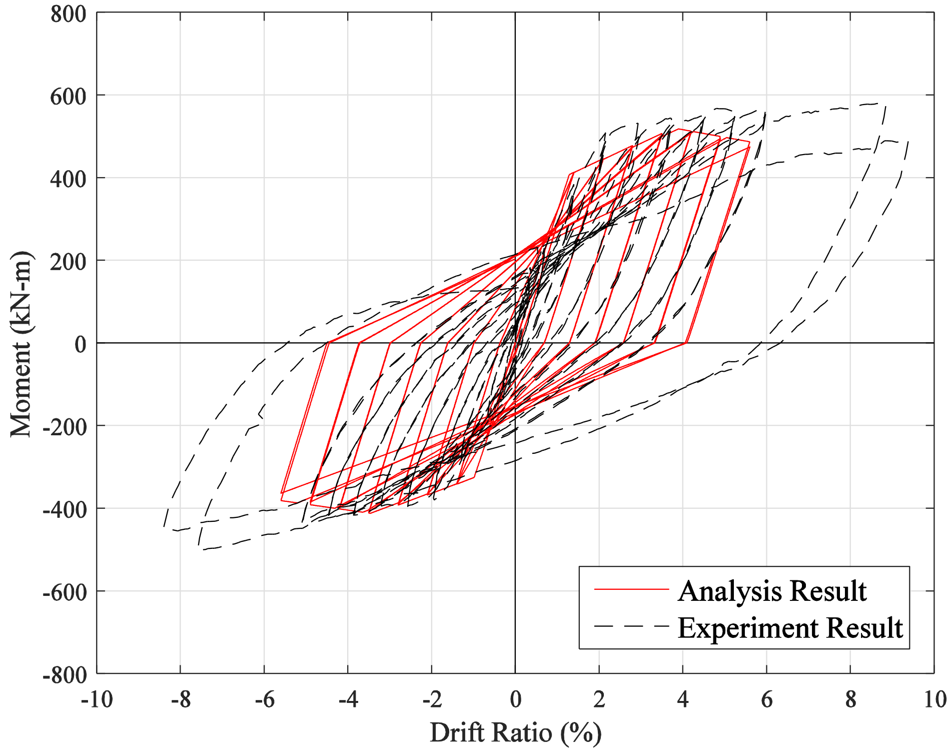

Fig. 6   Moment-drift ratio diagram of K-PT-N-2

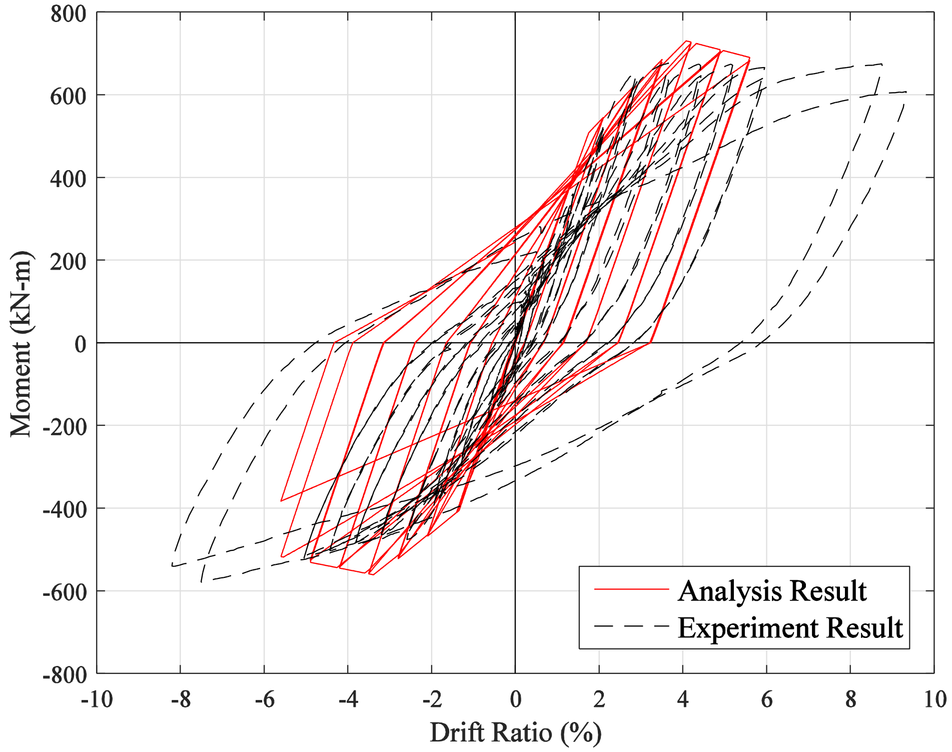

Fig. 7   Moment-drift ratio diagram of K-PT-N-3

Moment-drift diagrams show that the analysis results of each post-tensioned joint are in good agreement with the corresponding experimental results. The analysis model of K-PT-N-1 shows a little smaller moment capacity while the others do rather larger moment capacity. The analysis model of K-PT-N-2 also shows a little smaller positive moment capacity than the measured value, although it shows the almost same negative moment capacity. In the case of the analysis model of K-PT-N-3, the analysis result shows a rather larger moment capacities in both drifts: positive and negative.

All the analysis results show moderately higher initial rotational stiffness than the experiment results in the elastic range. The IMK deterioration model does not adjust the initial rotational stiffness in the elastic range.

Except the K-PT-N-3 analytical model, yielding moment values and plastic rotational capacity of experiments are larger than the analysis results. Given that actual yield strength of reinforcing bars is higher than the design strength (Kwon 2016), this could be considered as an analysis error. However, in the case of K-PT-N-3 analytical model, it shows the opposite result; analysis results show larger moment capacity than the experiment result. Particularly, after ±3% drift ratio, the error rate is increased. It appears as if the error exists during the calculation of the energy dissipation (i.e., error of the β value). According to the graph, the analytical model shows less energy dissipation than the experiment data.

Finally, although the same lateral seismic load condition is loaded based on given drift ratios, there is a difference between each excursion of both results. The experimental results show larger drift ratio in positive drift ratio and smaller drift ratio in negative drift ratio, compared to the analysis results in general. That would be caused by experimental errors from the actuator.

5. CONCLUSION

In this study, nonlinear analysis of post-tensioned reinforced concrete knee joints is carried out using the IMK pinching model in OpenSees. Based on the analysis results in comparison with experimental results, the following conclusions are drawn.

1. The nonlinear analysis using the IMK pinching model in OpenSees shows almost the same results as actual experimental data.
2. There are moderate differences in some parts of the analysis results compared with the experiment results. Nevertheless, the moment-drift ratio diagrams for experimental specimens show approximate resemblances.
3. The IMK deterioration model has been used for modeling steel and reinforced concrete elements. From this study, the IMK deterioration model could be an appropriate model for post-tensioned elements.
4. However, the research of modeling post-tensioned elements without calibrating with experiment results is not satisfactory. In the future, additional research is necessary for modeling post-tensioned elements, only using the material, section and element properties.

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