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DEVELOPMENT OF A SPECIMEN FOR PREDICTION OF PRESTRESS LOSSES IN CONTAINMENT BUILDING

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ABSTRACT

The prestressing force in a containment building decreases with time due to the immediate and time-dependent reasons such as anchorage slip and creep of concrete. Prediction of the prestress losses is very important but difficult task because of many uncertainties about concrete. In-service inspection(ISI) is conducted by the regulatory guide to check the prestressing force in the tendon but it has its limitations. Therefore, a new supplementary method to predict the prestress losses is developed and verified in this paper. The concept of the method is to make test specimens which represent some parts of the containment building and compare the behaviours of the specimens under the prestressing condition with the analysis results. If the loss of prestressing force of specimen predicted by the analysis corresponds with the loss of load experimentally measured from the specimen, it can be concluded that the analysis method and input parameters used for the analysis of the specimen are reasonable. Therefore, the long-term loss of the prestressing force in containment building can be predicted with less uncertainties by utilizing the analysis method and parameters decided from the test specimens. Details about the design of the specimen, analysis method, and experimental results are included in this paper. Development of the test specimens will be very helpful to predict the loss of prestressing force together with ISI and maintain structural integrity of the containment building.

INTRODUCTION

Containment building should prevent the leakage of radioactive materials (Pandey, 1997), protect the facilities from the external impact (BAE, et al., 2000) and maintain the structural integrity in the event of a major accident called loss of coolant accident(LOCA) (Lundqvist & Anderson, 2008). Most of containment buildings are prestressed concrete structures in order to withstand the tensile force caused by the design pressure. Therefore, the prestressing system directly affects the integrity of the containment building (Anderson, 2005). Prediction of the prestress losses is important but tricky because of many uncertainties of concrete.

Evaluations of prestress losses of bonded and unbonded prestressing systems are conducted by the regulatory guide. In case of the unbonded system, tendon forces are measured by the lift-off test. It only measures the force at the end of the tendon and its interpretation is controversial (Anderson, et al., 2005). For the bonded system, tendon forces are estimated by testing the prestressed beams. Flexural tests, destruction tests and lift-off tests of the beams are performed to estimate the tendon forces, but it is indirect method and has limitations.

Therefore, a new supplementary method to predict the prestress losses is developed. The concept of this method is to make a specimen which is modelled on a part of the containment building, and to have tests with this specimen instead of the beam. The specimen is tested under the same prestressing condition of the containment building and the prestressing force of the specimen is continuously measured by load cells. The prestress losses of the containment building can be estimated through the test results of the specimen.

This is a more direct method compared to the beam test for the prediction of the prestress losses. Details of the specimen and the analysis method are presented in the following sections.

DESIGN OF THE SPECIMEN

Figure 1 represents a part of the wall in a containment building, and its vertical and horizontal cross-sections with vertical and horizontal tendons. The specimen is modelled on this containment building which is one of the nuclear power plants in Korea. The specimen has a shape of cuboid whose vertical and horizontal cross-sections are decided based on the repeated tendons and rebars as marked with dotted square boxes in Figure 1. In other words, the specimen is the unit structure which represents a part of the wall. The specimen is scaled down by 1/2 for the test in laboratory. Tendons and rebars are also adjusted to have the same ratio of the original cross-section. Final design of the specimen is shown in Figure 2.

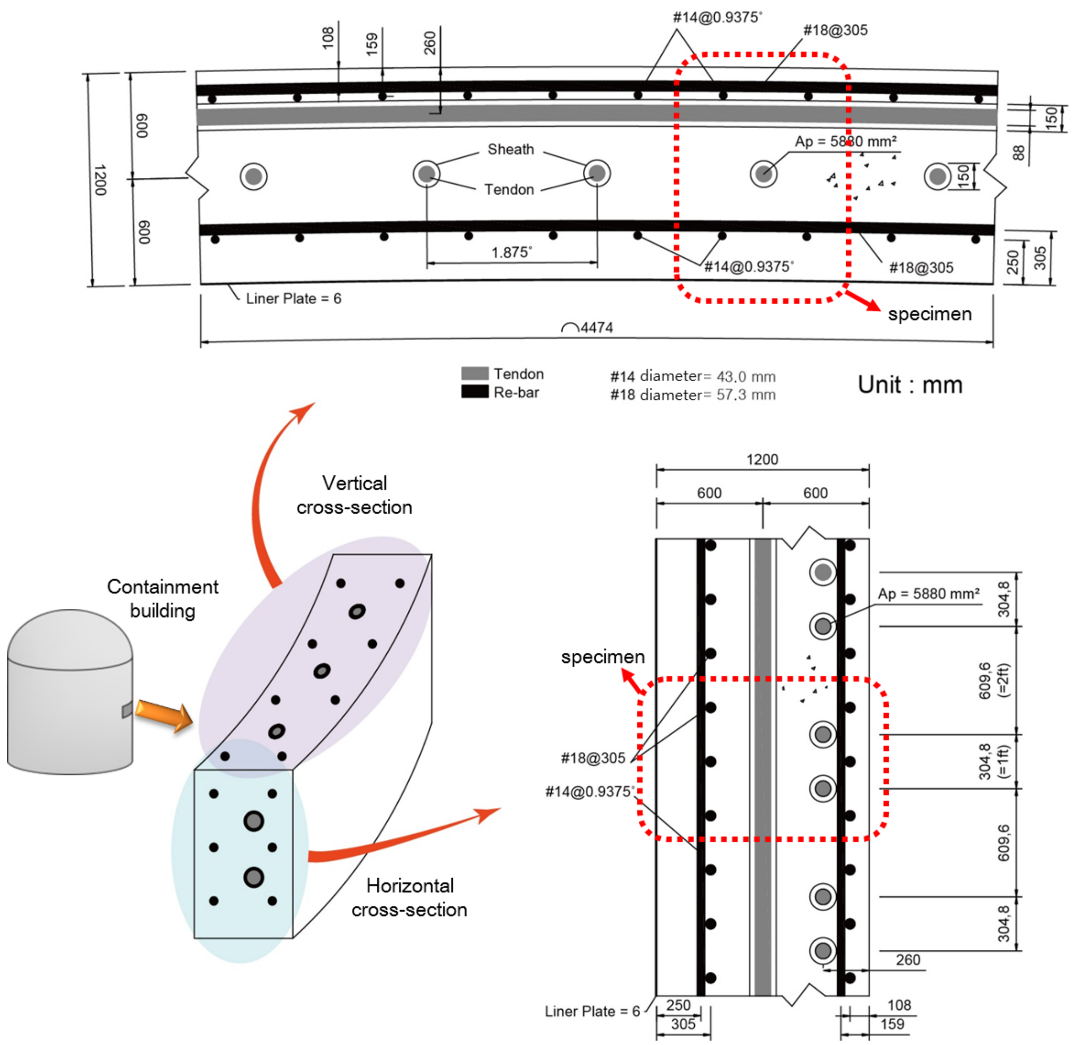
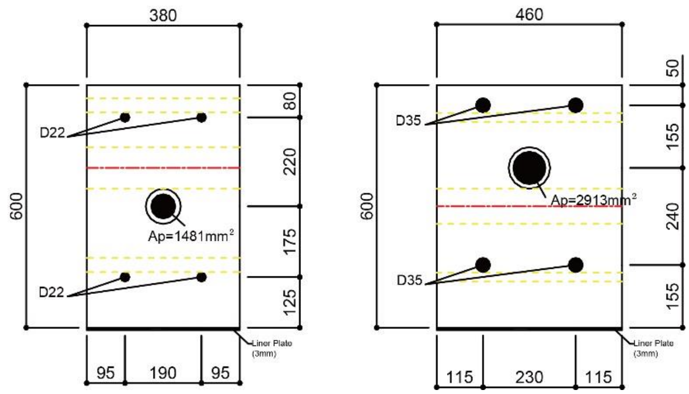


Figure 1. A part of a wall in a containment building



(a) (b)

Figure 2. Cross-sections of the specimen: (a) Vertical section; (b) Horizontal section

MATERIALS

Concrete

Concrete for the actual construction of the containment building is used for the specimen. The mixture of concrete is shown in Table 1.

Table 1: Mixture of concrete

w/b	Unit weight (kg/m^3)					
	W	*C*	*FA*	*S*	*G*	*SP*
0.4	163	326	81	749	939	2.6

Mechanical properties of concrete are determined by the experiments as shown in Table 2. Compressive strength and elastic modulus of concrete with moist and sealed curing are presented and these are used for the analysis of the specimen.

Table 2: Compressive strength and elastic modulus of concrete

Curing	Sealed					Moist
Age (day)	1	3	7	28	90	28
Compressive strength (MPa)	8.3	17.9	21.9	30.5	39.4	34.8
Elastic modulus (MPa)	11909	18017	19170	24170	27933	25241

Experiments for the long-term deformation of concrete are also conducted. Specimens with 100×100×400 mm dimensions were used for measuring drying shrinkage. Cylindrical specimens with ϕ150×300 mm dimensions were used for creep. Specimens were stored in rooms at temperature of 20℃ and relative humidity of 60%. Through the regression analysis of these experimental results by ACI model, Equation 1 and Equation 2 are obtained for drying shrinkage and creep. They are applied for the analysis of the specimen for predicting the prestress losses.

$$\varepsilon_{sh}(t) = 462.5 \times \frac{t}{5.3+t} \quad (\mu) \tag{1}$$

where ε_{sh} is drying shrinkage of concrete and t is the age of concrete since drying is started.

$$\phi(t-t') = 2.4 \times \frac{(t-t')}{8.9+(t-t')} \tag{2}$$

where ϕ is creep coefficient of concrete and t' is the age of loading.

Steel and Tendons

Rebars marked as 'D22' and 'D35' in Figure 2 are specified in Korean Industrial Standards(KS) (Korean Standard Association, 2011). Their mechanical properties are shown in Table 3. The numbers, 22 and 35, represent the diameter of the rebar.

Table 3: Specification of rebar

Elastic modulus (MPa)	Yield strength (MPa)	Ultimate strength(MPa)
200,000	400	560

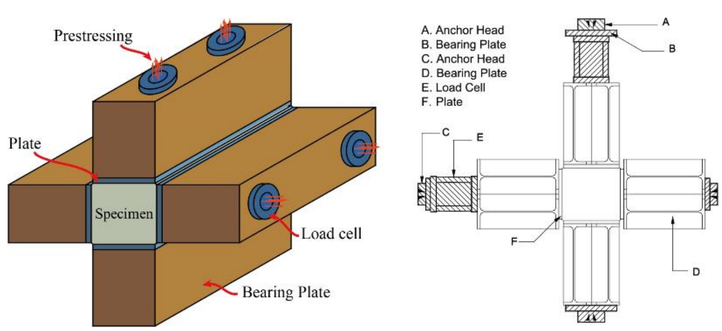
Tendon for the specimen which is a low relaxation strand called 'SWPC7BL 15.2mm' is also specified in KS (Korean Standard Association, 2011). Loss of stress due to relaxation of this tendon when the strain is restrained can be calculated by Equation (3) (PCI Committee on Prestress Losses, 1975).

$$f_r(t) = -\frac{f_p(t')}{45}[\log 24(t-t')]\left(\frac{f_p(t')}{f_{py}} - 0.55\right) \tag{3}$$

where f_r is loss of stress, $f_p(t')$ is initial stress applied to tendon, f_{py} is yield strength of tendon. Ultimate strength of the tendon used for the specimen is 1860MPa and the yield strength is 1580MPa which is 85% of the ultimate strength.

TEST SETUP

The bearing plates around the specimen are set up as shown in Figure 3 to have enough length for tendons to be prestressed. Anchor heads and load cells are place on top of the bearing plate. Tendons are passing through the bearing plates on both sides and sheath located in the specimen.



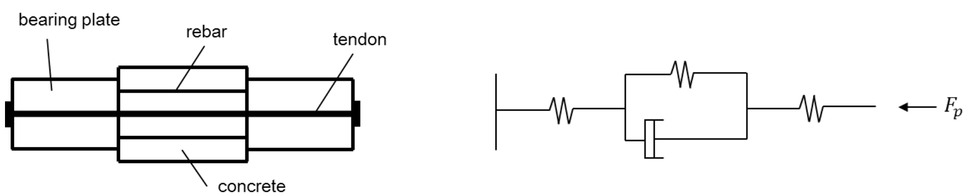
(a) (b)

Figure 3. Test setup: (a) 3D view; (b) Front view

Eccentric load is applied to the horizontal sections because tendons in horizontal sections are not located in the middle of the section as shown in Figure 2(a). Stress occurred under the eccentric load is different from that of the original containment building. Therefore, two specimens are aligned in one set of bearing plates as shown in Figure 3(a) in order to reduce the effect of eccentric load. It is also efficient way to conduct experiments of two specimens at one time.

PREDICTION OF PRESTRESS LOSS

The specimen is subjected to biaxial stress as shown in Figure 3(a). It can be simplified as Figure 4(a) if the uniaxial stress condition is assumed. The equivalent rheological model of Figure 4(a) can be a spring-dashpot system as shown in Figure 4(b). Bearing plates and rebars are made of steel, and their behaviour against the compressive stress is elastic. However, concrete can be expressed with a spring and a dashpot by Kelvin model because concrete has time-dependent deformation and it is not recovered as its initial state when unloading happens. Prestressing force can be regarded as an external loading applied to the structure. The force continuously decreases with time because of the relaxation.



(a) (b)

Figure 4. Simplified test structure: (a) Original structure; (b) Equivalent system

Step-by-step analysis is conducted to consider the time-dependent properties of concrete. Equation 4 represents the compatibility condition in x and y direction of i^{th} time step by considering the characteristics of the materials such as rebar, concrete and tendon.

$$\begin{bmatrix} \dfrac{\overline{f_{rx}(i)} - f_r(i)}{E_p} \\ \dfrac{\overline{f_{ry}(i)} - f_r(i)}{E_p} \end{bmatrix} = \frac{1}{E_c(1)} \begin{bmatrix} 1 & -\nu \\ -\nu & 1 \end{bmatrix}\begin{bmatrix} f_{cx}(1) \\ f_{cy}(1) \end{bmatrix}\phi(i,1) + \sum_{j=1}^{i-1}\frac{1}{E_c(j)}\begin{bmatrix} 1 & -\nu \\ -\nu & 1 \end{bmatrix}\begin{bmatrix} \Delta f_{cx}(j) \\ \Delta f_{cy}(j) \end{bmatrix}(1+\phi(i,j)) + \begin{bmatrix} \varepsilon_{shx}(i) \\ \varepsilon_{shy}(i) \end{bmatrix} + \frac{1}{E_b}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \Delta f_{bx}(i) \\ \Delta f_{by}(i) \end{bmatrix}$$

$$= \frac{1}{E_s}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \Delta f_{sx}(i) \\ \Delta f_{sy}(i) \end{bmatrix} + \frac{1}{E_b}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \Delta f_{bx}(i) \\ \Delta f_{by}(i) \end{bmatrix} \quad (4)$$

where f, E, ε, and ν are stress, elastic modulus, strain, and Poisson's ratio of concrete, respectively. The subscripts p, c, s, and b are the prestressed tendon, concrete, rebar, and bearing plate, respectively. $\overline{f_r}$ and f_r are the final loss of stress and the loss of stress of tendon itself calculated by Equation (3).

Left side of Equation 4 represents the change of strain in tendon caused by the deformation of the test structure. Right side of Equation 4 represents the sum of the strain in concrete and bearing plate. Concrete strain can replace with strain of rebar as shown in second line of Equation 4 because the strain of concrete and rebar are equal.

Force equilibrium in x and y direction can be formulated as shown in Equation 5.

$$\sum_{j=1}^{i-1}\begin{bmatrix} A_{cx} & 0 \\ 0 & A_{cy} \end{bmatrix}\begin{bmatrix} \Delta f_{cx}(j) \\ \Delta f_{cy}(j) \end{bmatrix} + \begin{bmatrix} A_{sx} & 0 \\ 0 & A_{sy} \end{bmatrix}\begin{bmatrix} \Delta f_{sx}(i) \\ \Delta f_{sy}(i) \end{bmatrix} = \begin{bmatrix} A_{bx} & 0 \\ 0 & A_{by} \end{bmatrix}\begin{bmatrix} \Delta f_{bx}(i) \\ \Delta f_{by}(i) \end{bmatrix} = \begin{bmatrix} -A_{px} & 0 \\ 0 & -A_{py} \end{bmatrix}\begin{bmatrix} \overline{f_{rx}}(i) \\ \overline{f_{ry}}(i) \end{bmatrix} \quad (5)$$

where A is the area and the meaning of subscripts are same as Equation 4.

Unknown variables $\overline{f_r(i)}$, $\Delta f_c(i-1)$, $\Delta f_s(i)$, and $\Delta f_b(i)$ are determined by solving the Equation 4 and Equation 5. The strain increment of concrete and bearing plate during i^{th} time step can be calculated by Equation 6. The final stress and strain of concrete, rebar, bearing plate, and prestressed tendon are calculated as shown in Equation 7 and Equation 8, respectively.

$$\Delta\varepsilon_c(i) = \Delta\varepsilon_s(i) = \Delta f_s / E_s \quad (6a)$$

$$\Delta\varepsilon_b(i) = \Delta f_b / E_b \quad (6b)$$

$$\varepsilon_s(i) = \varepsilon_c(i) = \varepsilon_s(1) + \Delta\varepsilon_s(i) \quad (7a)$$

$$\varepsilon_b(i) = \varepsilon_b(1) + \Delta\varepsilon_b(i) \quad (7b)$$

$$f_s(i) = f_s(1) + \Delta f_s(i) \quad (8a)$$

$$f_b(i) = f_b(1) + \Delta f_b(i) \quad (8b)$$

$$f_c(i) = f_c(i-1) + \Delta f_c(i-1) \quad (8c)$$

$$f_p(i) = f_p(1) - \overline{f_r(i)} \quad (8d)$$

where f_p is the stress of prestressed tendon.

COMPARISON OF THE PREDICTION AND EXPERIMENTAL RESULTS

The bearing plates do not have uniform sections. It is hard to find the equivalent area of the bearing plate for the analysis. Therefore, the areas of bearing plates A_{bx} and A_{by} are decided by comparing the calculated initial strains through the analysis with the instantaneous strains measured by strain gauge. The instantaneous strains of the bearing plates in both directions measured by the strain gauge and the areas of bearing plates A_{bx} and A_{bx} are shown in Table 4.

Table 4: Instantaneous strain and the area of bearing plate

	Horizontal section	Vertical section
Instantaneous measured strain(μ)	508	436
Calculated initial strain(μ)	507.97	436.3
Area of bearing plate(mm^2)	30000	19500

Figure 5 shows the comparison of the predicted results with the experimental results. It shows the similarity between them. Therefore, prestressing force in the real containment building can be predicted by using the same parameters used for the specimen except the parameters related with the size and initial prestressing force. Figure 6 shows the prestressing force predicted for a part of containment building explained in Figure 1. It is assumed that the tendons are prestressed by 65% of their ultimate strength. Compatibility condition and equilibrium condition are similar to Equation (4) and Equation (5), but the terms related with the bearing plates are eliminated. According to the analysis result, the prestressing forces are decreased after one year by 7 and 5 percent in horizontal and vertical direction, respectively. Prestressing forces are decreased by 9 and 7 percent after 3 years, and by 11 and 9 percent after 30 years. The ratio of the prestressing force to the initial one is presented in Figure 6(b). It is reasonable according to the measured prestress at Swedish nuclear reactor containments (Anderson, 2005). Anderson shows that the prestress loss after 30 years is generally between 5 and 10 percent.

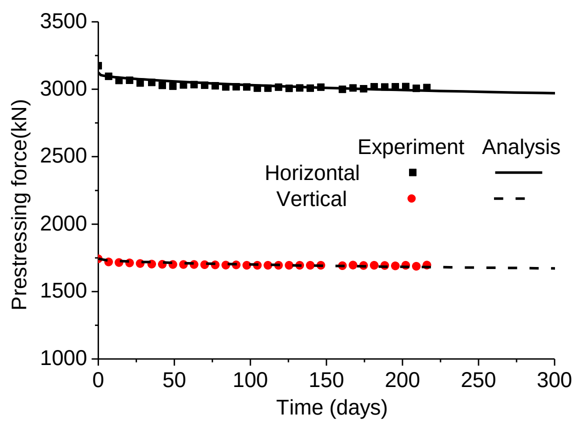


Figure 4. Comparison of predicted prestressing force with the measured force

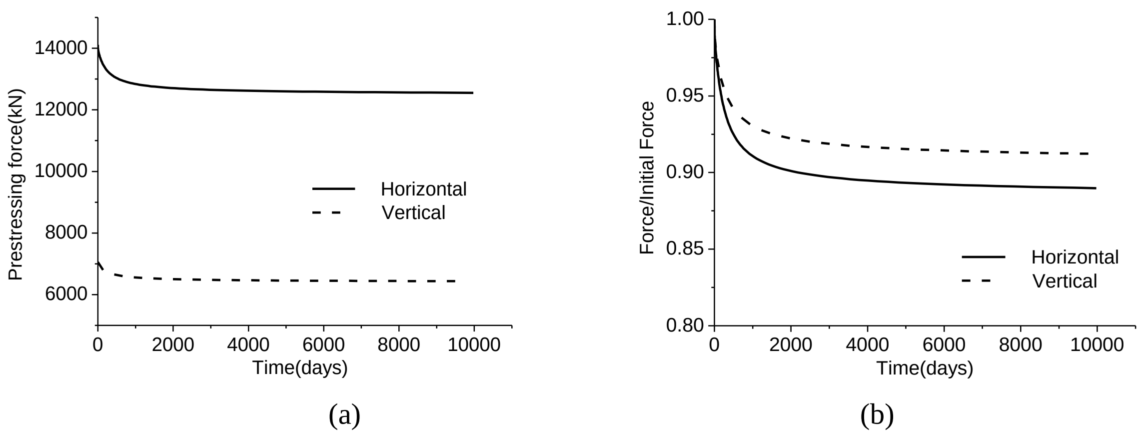


Figure 5. Prediction for the containment building: (a) Prestressing force; (b) Ratio of the force to its initial force.

CONCLUSIONS

A new method to predict the prestress loss in the containment building. It predicts the loss of prestress by observing the behaviour of the specimen which is made by imitating a part of the containment building. According to the analysis by the new method, prestressing force about 11 and 9 percent in horizontal and vertical section of the containment building are lost after 30 years. This is quite reasonable compared to the other researches. Although this paper only includes the test result of one type of specimen, the more types of specimen are tested, the better prediction for the whole behaviour of the tendon is possible.

The specimen can reflect the field conditions same as the nuclear reactor containment. Also, it is more direct experiment compared to the beam test. Therfore, development of the specimen and analysis methods can be very useful for the in-service inspection, especially for the bonded prestressing system. More studies are necessary to verify the method and apply to the field.

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REFERENCES

Anderson, P. (2005). "Thirty years of measured prestress at Swedish nuclear reactor containments," *Nuclear Engineering and Design,* 235(21), pp. 2323-2336.
Anderson, P., Berglund, L. E. and Gustavsson, J. (2005). "Average force along unbonded tendons: A field study at nuclear reactor containments in Sweden," *Nuclear Engineering and Design,* 235(1), pp. 91-100.
BAE, I., CHOI, I. and SEO, J. (2000). "Nonlinear Flexural Analysis of PSC Test Beams in CANDU Nuclear Power Plants," *Journal of the Korean Nuclear Society,* 32(2), pp. 180-190.
Korean Standard Association. (2011). *Steel bars for concrete reinforcement (KS D 3504).* s.l.:Korean Industrial Standards.
Korean Standard Association. (2011). *Uncoated stress-relieved steel wires and strands for prestressed concrete (KS D 7002).* s.l.:Korean Industrial Standards.
Lundqvist, P. and Anderson, P. (2008). "Measured Loss of Prestress in 30-Year-Old Concrete Structures," *CSNI Workshop: Ageing Management of Thick Walled Concrete Structures.*
Pandey, M. (1997). "Reliability-based assessment of integrity of bonded prestressed concrete containment structures," *Nuclear Engineering and Design,* 176(3), pp. 247-260.
PCI Committee on Prestress Losses. (1975). "Recommendations for estimating prestress losses," *PCI Journal*, pp. 43-75.