Bond Strength of Mortar-filled Steel Pipe Splices Reflecting Confining Effect

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Abstract

This study purposed to evaluate the adequacy of existing equations proposed for calculating the bond strength of reinforcing bar splices in a mortar-filled steel pipe sleeve, and to propose a method for estimating the bond strength of bar splices that quantitatively reflects the confining effect of a steel pipe sleeve. For this purpose, we analyzed a total of 40 experimental mortar-filled steel pipe splices in which bond failure occurred, and examined how the confinement effect of steel pipe affects the bond performance of these splices.

The study results showed that existing methods of estimating the bond strength of the bar splices did not adequately estimate the bond strength of reinforcement splices in a mortar-filled steel pipe sleeve. In addition, based on the results of the tests on the 40 analyzed specimens, we performed multiple regression analysis with independent variables such as sleeve shape and the development length of a bar, and proposed the confining pressure of mortar-filled steel pipe splices. By applying the proposed confining pressure to Untrauer and Henry's bond strength equation reflecting the lateral confining pressure, we computed the bond strength of mortar-filled steel pipe splices more accurately than existing bond strength estimation methods.

Keywords: steel pipe sleeve; mortar-filled; reinforcing bar splices; confining effect; bond strength

1. Introduction

In a reinforcing bar splice in a mortar-filled sleeve, which is one of the most common reinforcement splicing methods used for reinforced concrete structures, bond strength between infilled mortar and bars is the most important structural performance. In such a reinforcing bar splice, where the bars and the sleeve become one body by the infilled mortar, the sleeve through which force is transmitted from rebars on one side to those on the other side confines the infilled mortar surrounding the bars inside the sleeve. The lateral confining action is known to increase bond strength between the reinforcements and surrounding mortar. Accordingly, in order to estimate bond strength between infilled mortar and reinforcing bars in mortar-filled sleeve bar splices adequately, we need to consider the confining effect of the sleeve. In response to this need, recently the author (2008) measured the confining effect of the sleeve in mortar-filled steel pipe bar splices quantitatively through experimental research, and published the results. The objective of the present paper is to propose a method of estimating bond strength more reasonably by reflecting the confining effect of the sleeve in the equation for calculating the bond strength of reinforcing bar splices in the mortar-filled steel pipe sleeve.

There have been few studies thus far on the bond strength between infilled mortar and bars in mortar-filled sleeve splices. Among the previous studies, Hayashi et al. (1994) made experimental mortar-filled steel pipe splices with strain gauges attached to the sleeve surface and embedded bars of the specimens, and conducted a monotonic loading test using experimental variables such as the development length of bars and the compressive strength of infilled mortar. From the test results, the researchers derived the bond characteristic between reinforcements and infilled mortar and proposed a method of estimating the bond strength of the reinforcing bar splices, but their bond strength equation did not consider the confining effect of the sleeve. In addition, Einea et al. (1995) prepared specimens of mortar-filled steel pipe splices with small-diameter bars (D16, D19) embedded in the sleeve and with a strain gauge attached to the surface of the sleeve, and performed a monotonic loading and estimated the confining action of the sleeve with regard to bond strength between bars and infilled mortar in the specimens. However, this study did not proceed until proposing an equation for calculating the bond strength of the reinforcing bar splices reflecting the confining...
effect of the sleeve. On the other hand, Kim and Ahn (2003) prepared experimental reinforcing bar splices in the mortar-filled cast sleeve using bars D19 and D25, and measured the lateral confining effect of the cast sleeve quantitatively. They studied how the calculated confining action of the sleeve working on mortar-filled cast sleeve splices affects the bond strength of these bar splices, and then proposed an equation for calculating the bond strength of bar splices in the mortar-filled cast sleeve.

As shown in the previous research listed above, existing methods of estimating the bond strength of reinforcing bar splices in the mortar-filled sleeve did not reflect the confining effect of the sleeve. Even though reflecting it, these existing methods were derived from the results of monotonic loading tests that used specimens built with small-diameter bars (D25 or smaller). For this reason, it is hard to say that these methods are adequate for estimating the bond strength of reinforcing bar splices. Thus, in order to propose a more reasonable bond strength equation that reflects the confining effect of the sleeve in mortar-filled sleeve splices, it is considered necessary to carry out research with more diverse variables.

Thus, this study evaluated the adequacy of previously proposed equations for estimating the bond strength of mortar-filled reinforcing bar splices using test results on 15 specimens in which bond failure finally occurred. In the specimens, the development length of the reinforcing bar ranged between 3.7~8d (d is the nominal diameter of bars) and the compressive strength of infilled mortar ranged between 45~84MPa. In addition, 4 types of bar were used including SD400 and SD500, 7 types of bar size were used including D25, D32 and D35, and two types of loading were used including monotonic and cyclic loading. Moreover, the experimental data of 5 research teams were used for analysis.

The author's research team (2007, 2008) developed a reinforcing bar splice in a steel pipe sleeve using high-strength bar SD500, and in order to measure structural performance such as the tensile strength and confining effect of the bar sleeve splice, we built 43 full-scale experimental reinforcing bar splices in a steel pipe sleeve, including 15 specimens with a strain gauge attached to the surface of the sleeve. Then, we performed monotonic and cyclic loading with the specimens. Experimental variables included the development length of bars in the sleeve, the compressive strength of infilled mortar, and the bar size. In the test, the final failure mode of the specimens was reinforcement fracture in 22 specimens, sleeve fracture in 6, and bond failure in 15. Fig.1 shows the representative sleeve shapes used in the specimens.

Hayashi et al. (1994, 1997) conducted an experiment in order to assess structural performance and bond performance between mortar and bars in mortar-filled sleeve splices prepared using the deformed steel pipes. The major test variables were the development length of bars, the compressive strength of infilled mortar, and the bar size.

Einea et al. (1995) executed a monotonic loading test in order to determine the tensile strength of mortar-filled steel pipe splices and the confinement effect of the sleeve. The test variables included the shape of the steel pipe sleeve, the development length of bars, and the compressive strength of filling grout. Fig.2 shows the sleeve shape used in the specimens.

Lee et al. (1997) developed a reinforcing bar splice using steel pipes for pressure piping, and conducted a monotonic loading test to assess the structural performance of the bar splice, including tensile

2. Analyzed Specimens

Table 1. shows the data on specimens analyzed in this study. The specimens were 40 reinforcing bar splices in the mortar-filled steel pipe sleeve in which bond failure occurred, we analyzed how the confining action of the steel pipe sleeve is affected by the major structural factors of mortar-filled steel pipe splices, and then proposed a method of computing the bond strength of these reinforcing bar splices that reflects the confining effect of the steel pipe sleeve quantitatively.
strength. The major variables of the test were the shape of bosses inside the steel pipe, the development length of bars, etc.

Lee and Yi (2004) conducted a monotonic loading test in order to assess the structural performance of reinforcing bar splices in the steel pipe sleeve prepared using bars D29~D35. The test variables were the diameter and thickness of the sleeve, the shape of thread, the development length of bars, etc.

### 3. Evaluation of Test Results with Existing Equations for the Bond Strength of Reinforcing Bar Splices in Mortar-filled Sleeve

This section evaluated the adequacy of two existing methods for estimating the bond strength of reinforcing bar splices in the mortar-filled sleeve using 40 mortar-filled steel pipe splices in which bond failure occurred. As shown in Table 1, the yield strength of the bar splices was obtained from the results of material testing. However, because there were no results concerning the yield strength of reinforcing bars based on statistical data from reinforcing bar tests in the reference (Architectural Institute of Japan, 1990), development length of bar, thickness of steel pipe, inner diameter of steel pipe, inner diameter of end opening in steel pipe, compressive strength of mortar, maximum load of specimens

Table 1. Specimens Analyzed in this Study

| No. | Representative tester | Specimen name | Size | $\sigma_y$ (MPa) | $f_{cm}$ (MPa) | Loading method | $P_{max}$ (kN) |
|-----|-----------------------|---------------|------|----------------|----------------|--------------|----------------|
| 1   | The author            | 37B2NM-1      | D35  | 556           | 7.5            | M            | 539.9         |
| 2   | The author            | 37B2HM-1      | D35  | 556           | 7.5            | M            | 530.2         |
| 3   | The author            | 47B2NM-1      | D35  | 579           | 7.5            | M            | 718.8         |
| 4   | The author            | 47B2HM-1      | D35  | 579           | 7.5            | M            | 685.0         |
| 5   | The author            | 17A1NC-1      | D19  | 590           | 7.5            | C            | 197.2         |
| 6   | The author            | 37B2HC-1      | D35  | 556           | 7.5            | M            | 554.9         |
| 7   | The author            | 47B2NC-1      | D35  | 579           | 7.5            | C            | 704.1         |
| 8   | The author            | 47B2HC-1      | D35  | 579           | 7.5            | C            | 707.3         |
| 9   | The author            | 35B2NM-1      | D35  | 556           | 5.0            | M            | 441.8         |
| 10  | The author            | 35B2NM-2      | D35  | 556           | 5.0            | M            | 404.8         |
| 11  | The author            | 35B2NM-3      | D35  | 556           | 5.0            | M            | 445.7         |
| 12  | The author            | 35B2HM-1      | D35  | 556           | 5.0            | M            | 443.3         |
| 13  | The author            | 35B2HM-2      | D35  | 556           | 5.0            | M            | 440.2         |
| 14  | The author            | 35B2NC-1      | D35  | 556           | 5.0            | C            | 442.4         |
| 15  | The author            | 35B2NC-2      | D35  | 556           | 5.0            | C            | 357.3         |
| 16  | Hayashi (1994, 1997)  | No.1          | D35  | 470           | 3.7            | M            | 374.4         |
| 17  | Hayashi (1994, 1997)  | No.2          | D35  | 470           | 5.0            | M            | 516.1         |
| 18  | Hayashi (1994, 1997)  | No.3          | D35  | 470           | 5.0            | C            | 529.3         |
| 19  | Hayashi (1994, 1997)  | No.4          | D35  | 470           | 5.0            | M            | 537.7         |
| 20  | Hayashi (1994, 1997)  | No.5          | D35  | 470           | 5.0            | C            | 505.8         |
| 21  | Hayashi (1994, 1997)  | No.6          | D35  | 470           | 5.0            | M            | 552.1         |
| 22  | Einea (1995)          | TY-3-2        | D19  | 484           | 67             | M            | 105.2         |
| 23  | Einea (1995)          | TY-3-3        | D19  | 484           | 8.0            | M            | 113.3         |
| 24  | Einea (1995)          | TY-4-1        | D19  | 484           | 8.0            | M            | 133.3         |
| 25  | Einea (1995)          | TY-4-2        | D19  | 484           | 8.0            | M            | 197.7         |
| 26  | Einea (1995)          | TY-4-3        | D19  | 484           | 8.0            | M            | 146.5         |
| 27  | L. Lee (1997)         | 3STN25-2      | D22  | 392           | 6.5            | M            | 208.9         |
| 28  | L. Lee (1997)         | 3STN25-3      | D25  | 344           | 5.7            | M            | 267.4         |
| 29  | L. Lee (1997)         | 3STN25-4      | D25  | 344           | 5.7            | M            | 264.9         |
| 30  | L. Lee (1997)         | 3STN55-1      | D25  | 344           | 5.7            | M            | 245.1         |
| 31  | L. Lee (1997)         | 3STN55-2      | D25  | 344           | 5.7            | M            | 261.5         |
| 32  | L. Lee (1997)         | 2STN67-1      | D22  | 392           | 6.5            | M            | 210.4         |
| 33  | L. Lee (1997)         | 2STN67-2      | D22  | 392           | 6.5            | M            | 211.5         |
| 34  | L. Lee (1997)         | 2STN67-3      | D22  | 392           | 6.5            | M            | 250.0         |
| 35  | L. Lee (1997)         | 3STN67-2      | D25  | 344           | 5.7            | M            | 266.4         |
| 36  | L. Lee (1997)         | 3STN69-1      | D25  | 344           | 5.7            | M            | 264.9         |
| 37  | L. Lee (1997)         | 3STN69-2      | D25  | 344           | 5.7            | M            | 269.4         |
| 38  | Y. Lee (2004)         | 4MC625        | D29  | 733           | 6.6            | C            | 345.3         |
| 39  | Y. Lee (2004)         | 5MC735        | D32  | 386           | 7.0            | C            | 402.0         |
| 40  | Y. Lee (2004)         | 5MC737        | D32  | 386           | 7.0            | C            | 409.8         |

(1): Yield strength of bar, based on the results of material testing. However, because there were no results concerning the material testing of reinforcing bars in Einea's experiment (5 specimens), we assumed the yield strength of reinforcing bars based on statistical data from reinforcing bar tests in the reference (Architectural Institute of Japan, 1990). (2): Development length of bar, (3): Thickness of steel pipe, (4): Inner diameter of steel pipe, (5): Inner diameter of end opening in steel pipe, (6): Compressive strength of mortar, (7): Cyclic loading, (8): Maximum load of specimens.
where $D$ is nominal diameter of bars (cm), $L$ is development length of bars (cm), $l$ is distance from the end of the steel pipe to the first lug of the reinforcing bar (assumed to be 0.7D), and $F_g$ is compressive strength of grout mortar (kgf/cm$^2$).

On the other hand, using cast sleeve splices in which bond failure occurred, Kim and Ahn (2003) proposed Eq. (5)~(7) (referred to as Kim's equation hereinafter), which considers the tangential confining effect of the sleeve, for estimating bond strength between bars and mortar under the maximum load. Among them, Eq. (6) was an equation derived by changing Untrauer and Henry's bond strength equation (1965), which reflects the lateral confining effect, to the SI unit. Here, bond stress distribution between bars and infilled mortar was assumed to be constant over the whole length of the bar embedded in the sleeve.

$$P_{\text{max}} = \tau \cdot \pi \cdot d \cdot \ell$$

$$\tau = (1.49 + 0.45 \sqrt{f_n}) \sqrt{f_m}$$

$$f_n = 56 - 5.7(\ell / d) - 0.15 f_m$$

where $\tau$ is bond strength of mortar-filled sleeve splices (N/mm$^2$), $d$ is the nominal diameter of bars (mm), $\ell$ is the development length of bars (mm), $f_n$ is the lateral confining pressure (N/mm$^2$), and $f_m$ is the compressive strength of infilled mortar (N/mm$^2$).

3.2 Evaluation of test results with existing equations for the bond strength of the bar splices

We calculated the bond strength of the 40 specimens in which bond failure occurred using the two existing estimation methods described above, and compared the test results as shown in Fig. 3. Table 2 shows the mean value and the variation coefficient of $P_{\text{test}}/P_{\text{cal.}}$, the ratio of the experimental value to the calculated value obtained using the two existing bond strength estimation methods. Hayashi's equation overestimated the bond strength of the 40 bar splice specimens by around 17%, and the coefficient of variation was 12.7%. On the other hand, using Kim's equation, the mean value of $P_{\text{test}}/P_{\text{cal.}}$ was 1.01 for the 40 specimens, but the coefficient of variation was 22.5%, showing a larger variation than Hayashi's equation in predicting experimental values.

Fig. 3 and Table 2 compared the 40 specimens without classification according to variables affecting the bond strength of the specimens, but we need to classify and analyze test data according to variables affecting the bond strength. Therefore, for experimental variables that were expected to affect the bond strength of the reinforcing bar splices, we analyzed comparatively $P_{\text{test}}/P_{\text{cal.}}$ obtained by the two existing estimation methods mentioned above. Fig. 4 compared $P_{\text{test}}/P_{\text{cal.}}$ obtained from the two equations according to the development length of bars in order to measure the effect of the development length embedded in the sleeve. The specimens compared in this figure, which were from 3 research groups, were almost identical in all conditions except for the development length of bars. As shown in Fig. 4, Hayashi's equation overestimated bond strength by more than 15% as a whole, but deviation according to the development length of bars was relatively small. On the other hand, Kim's equation, though varying according to specimen type, underestimated bond strength more with an increase in the development length of bars, and consequently, deviation according to development length was large. In Fig. 5., we compared $P_{\text{test}}/P_{\text{cal.}}$ obtained by the two methods.

Table 2. Statistics on the Ratio of Experimental Value/Calculated Value ($P_{\text{test}}/P_{\text{cal.}}$) by Existing Equations for Estimating the Bond Strength of Bar Sleeve Splices

| Statistics | Hayashi's equation | Kim's equation |
|------------|--------------------|----------------|
| Mean       | 0.854              | 1.005          |
| Standard deviation | 0.108              | 0.227          |
| Coefficient of variation (%) | 12.7              | 22.5           |

Fig.3. Comparison between Experimental Values and Values Calculated by Existing Equations for Estimating the Bond Strength of the Sleeve Bar Splices
obtained by the two equations in order to examine the effect of sleeve shape on the two existing bond strength estimation methods. The specimens compared in this figure, which were from the research group of Einea et al., were identical in all conditions except for sleeve shape. Here, Hayashi's equation and Kim's equation showed deviation in bond strength according to the ratio of sleeve thickness to inner diameter of the sleeve (t/d) and the ratio of the inner diameter of the sleeve end opening to the diameter of embedded bars (d_e/d_i). In Fig.6., we compared \( P_{\text{test}}/P_{\text{cal}} \) obtained by the two equations in order to examine the effect of the compressive strength of infilled mortar on the two existing bond strength estimation methods. The specimens compared in this figure, which were from the research group of Einea et al. (1995), were identical in all conditions except for the compressive strength of mortar. Here, Hayashi's equation showed little deviation according to the compressive strength of mortar but overestimated bond strength by more than 30%, but with a decrease in the compressive strength of mortar, Kim's equation overestimated bond strength more, and consequently, showed a larger deviation according to the compressive strength of mortar.

As presented above, the two existing bond strength estimation methods did not estimate the bond strength
of reinforcing bar splices in the mortar-filled steel pipe sleeve adequately. For this reason, we need to propose a more adequate method of estimating the bond strength of the bar splices.

4. Method of Estimating the Bond Strength of the Steel Pipe Splices that Reflects the Confining Effect

4.1 Bond performance reflecting the confining effect of the steel pipe sleeve

In the recent research published by the author (Kim, 2008), in order to determine the confining effect of the sleeve in mortar-filled steel pipe splices, we examined how the bond performance of these splices is affected by the confinement effect of the steel pipe sleeve by preparing full-scale specimens of steel pipe splices with a strain gauge attached to the surface of the sleeve and conducting a loading test. From the distribution of strain measured on the surface of the sleeve, we calculated the confining pressure working on the reinforcing bar splices using Eq. (8) below, and then computed overall bond strength as in Eq. (9) by applying the confining pressure to Eq. (6), which is Untrauer and Henry’s bond stress equation reflecting the lateral confining effect. According to the results as shown in Table 3., the equation estimated the experimental value within an error range of 5%.

\[
f_n = \frac{2E_{ss}}{1 - \nu_{sx} \cdot \nu_{sy}} \left( \frac{\tau \cdot \pi \cdot d_i}{d_i} \right) f_m^{0.5}
\]

where \(E_{ss}\) is the tangential modulus of elasticity of the sleeve, \(\nu_{sx}\) is the tangential Poisson ratio of the sleeve, \(\nu_{sy}\) is the axial Poisson ratio of the sleeve, \(\tau\) is the tangential strain working on the sleeve, \(\tau\) is the axial strain working on the sleeve, \(t\) is the thickness of the sleeve, and \(d_i\) is the inner diameter of the sleeve

\[
P_{b, com} = \int_{d_i}^{d_f} \left( \tau \cdot \pi \cdot d_i \right) dx
\]

where \(L_d\) is the development length of bars (mm), \(\tau\) is bond stress of the mortar-filled bar splice calculated by Eq. (6), \(d_i\) is nominal diameter of embedded bars (mm), and \(dx\) is the tiny part of the development length of bars (mm).

4.2 Proposed method of estimating the bond strength of the steel pipe splices

As described above, Eq. (6) estimated bond strength with tangential confining pressure relatively accurately. In this aspect, Eq. (6) is considered usable as a bond strength estimation method for reinforcing bar splices in the mortar-filled sleeve. If we know the actual bond stress and mortar compressive strength of a reinforcing bar splice in a mortar-filled steel pipe sleeve in which bond failure occurred, we can calculate the confining pressure of the splice even if it does not have a strain gauge on the surface of the sleeve. That is, from Eq. (6), tangential confining pressure \(f_c\) can be expressed as follows.

\[
f_n = 4.94 \left( \frac{\tau}{\sqrt{f_m}} \right)^2 - 14.72 \frac{\tau}{\sqrt{f_m}} + 10.96
\]

where \(\tau\) is the maximum bond stress of the specimen (N/mm²) and \(f_m\) is the compressive strength of mortar (N/mm²)

By applying Eq. (10) above to the 40 specimens analyzed in this study, which showed bond failure at the end, we can calculate the tangential confining pressure of each specimen. Here, the tangential confining pressure \(f_c\) of each specimen was obtained through multiple regression analysis using the following independent variables: the ratio of sleeve thickness to inner diameter of the sleeve (\(t/d_i\)), the ratio of the inner diameter of sleeve end opening to the diameter of embedded bars (\(d_i/d\)), the ratio of the development length of bars to the bar diameter (\(U/d\)), the compressive strength of infilled mortar (\(f_m\)), the yield strength of embedded bars (\(f_y\)), and the nominal diameter of bars (\(d\)).

\[
f_n = A + B \frac{f_m}{d} + C \left( \frac{U}{d} \right) + D \left( \frac{f_y}{d} \right) + E \cdot f_m + F \cdot f_y + G
\]

where A, B, C, D, E, F, and G are the coefficients, \(t\) is the thickness of the sleeve, \(d_i\) is the inner diameter of the sleeve, \(d\) is the inner diameter of the sleeve end opening, \(d_i\) is the inner diameter of bars, \(t\) is the development length of bars, \(f_m\) is the compressive strength of infilled mortar (MPa), and \(f_y\) is the yield strength of embedded bars (MPa)

The ratio of sleeve thickness to inner diameter of the sleeve and the ratio of the inner diameter of the sleeve end opening to the diameter of embedded bars were used as independent variables of tangential confining pressure \(f_c\) because the two sleeve shapes above were found to affect the bond strength of the sleeve. In particular, the ratio of sleeve thickness to inner diameter of the sleeve is a variable included in Eq. (8), which is used to estimate the confining pressure of the bar splice. The ratio of the development length of bars to the bar diameter was used because, as shown in
previous research on the confining effect of the sleeve (Ahn et al., 2003; Kim, 2008), the variable was found to have a significant effect on tangential confining pressure. The compressive strength of infilled mortar was adopted as a variable because while it is difficult to assert the direct effect due to a lack of previous research comparing the tangential confining pressure of the sleeve according to the compressive strength of mortar, it may affect the bond behavior of specimens such as failure mode and bond stress distribution, and consequently, was expected to affect the tangential confining effect of mortar-filled bar splices. In addition, the yield strength of embedded bars was used as an independent variable of tangential confining pressure because depending on the grade of embedded bars in the sleeve, the bond stress between the reinforcing bars and infilled mortar may differ, which may cause a difference in the radial stress of the bars, and consequently, a difference in the confining pressure of the sleeve. Finally, the nominal diameter of embedded bars was also adopted as an independent variable of tangential confining pressure because bond stress may differ according to the bar size.

In the results of the multiple regression analysis above, the values of the coefficients in the equation were $A=169.60$, $B=-14.04$, $C=-2.17$, $D=-0.053$, $E=0.0229$, $F=-0.446$, and $G=35.3$. To simplify the equation, the values of the coefficients were adjusted to $A=170$, $B=-14$, $C=-2.2$, $D=-0.05$, $E=0.023$, $F=-0.45$, $G=35$. Then, Eq. (12) below is obtained.

$$f_n = 170\left(\frac{\ell}{d_i}\right) - 14\left(\frac{\ell d}{d_i}\right) - 2.2\left(\frac{\ell}{d}\right) - 0.05 f_n + 0.023 f_y - 0.45 d + 35$$

(12)

If the distribution of bond stress between reinforcing bars and infilled mortar is assumed to be constant over the whole length of the bars embedded in the sleeve, the bond strength of the steel pipe sleeve splices can be calculated as follows.

$$P_{\text{cal}} = \sum_o \cdot \ell \cdot \tau$$

(13)

where $\Sigma_o$ is the circumference of bars (mm), $\ell$ is the development length of bars embedded in the sleeve (mm), and $\tau$ is bond stress obtained by Eq. (6) (N/mm²).

Using the 40 specimens with final bond failure, we calculated tangential confining pressure by Eq. (12) above, and then calculated the bond strength of each specimen by substituting the tangential confining
5.1\% obtained by the proposed equation for the 40 specimens was 1.007, the coefficient of variation was 5.1\%, and 95\% confidence interval was 0.907~1.107. On the other hand, as mentioned earlier, when the existing bond strength estimation method of Hayashi’s equation was used, the mean value of $P_{\text{cal.}}/P_{\text{est.}}$ was 0.854, the coefficient of variation was 12.7\%, and 95\% confidence interval was 0.641~1.067, and when Kim’s equation was used, the mean value of $P_{\text{cal.}}/P_{\text{est.}}$ was 1.005, the coefficient of variation was 22.5\%, and 95\% confidence interval was 0.561~1.450. Accordingly, compared to existing bond strength estimation methods, the proposed equation estimated the bond strength of reinforcing bar splices in the mortar-filled steel pipe sleeve more accurately. In addition, Fig.7. shows that for the 40 specimens, the proposed equation did not show a deviation according to the ratio of sleeve thickness to inner diameter of the sleeve (t/d), the ratio of the inner diameter of the sleeve end opening to the diameter of embedded bars (d/d), the ratio of the development length of bars to the bar diameter (L/d), and the compressive strength of infilled mortar ($f_c$). Although not included in the figure, moreover, the equation proposed above was found to have no deviation according to the yield strength of embedded bars ($f_y$) and the nominal diameter of bars (d) for the experiment data examined in this study.

5. Conclusions

This study aimed to evaluate the adequacy of existing equations proposed to estimate the bond strength of reinforcing bar splices in the mortar-filled steel pipe sleeve, and to propose a new method of estimating the bond strength of such bar splices that reflects the confining effect of the steel pipe sleeve quantitatively. To achieve this, we examined the results of 40 mortar-filled steel pipe splices in which bond failure finally occurred, including 15 prepared and tested by the author, and drew the following conclusions.

1) The existing methods for estimating the bond strength of reinforcing bar splices in the mortar-filled sleeve overestimated the bond strength of reinforcing bar splices of the mortar-filled steel pipe sleeve by more than 15\%, or showed a large deviation in predicting the experimental values according to test variables. Consequently, they did not assess the bond strength of the bar splices adequately.

2) Using the test results on the 40 bond-failed specimens analyzed in this study, we performed multiple regression analysis with independent variables such as sleeve shape, the development length of bars, and the compressive strength of infilled mortar and proposed the confining pressure of reinforcing bar splices in the steel pipe sleeve. By applying the proposed confining pressure equation to Untrauer and Henry’s bond strength equation reflecting lateral confining effect, we could estimate the bond strength of reinforcing bar splices in the mortar-filled steel pipe sleeve more accurately than existing bond strength estimation methods.

References

1) Kim, H. (2008) Confining Effect of Mortar-Filled Steel Pipe Splice, Architectural Research, Architectural Institute of Korea, Vol. 10, No. 2, December 2008, pp.27-35.
2) Hayashi, Y., Shimizu, R., Nakatsuka, T. and Suzuki, K. (1994) Bond Stress-Slip Characteristics of Reinforcing Bars in Grout-Filled Coupling Steel Sleeves, Journal of Structural and Construction Engineering, Architectural Institute of Japan, No. 462, August 1994, pp.131-139. (in Japanese).
3) Einea, A., Yamane, T. and Tadros, M. K. (1995) Grout-Filled Pipe Splices for Precast Concrete Construction, PCI Journal, January-February 1995, pp.82-93.
4) Kim, H. and Ahn, B. (2003) Bond Strength of Grout-Filled Splice Sleeve Considering Effects of Confinement, Journal of the Korea Concrete Institute, Vol. 15, No. 4, August 2003, pp.615-622. (in Korean).
5) Lee, S. and Kim, H. (2007) Development of Steel Pipe Splice Sleeve for High Strength Reinforcing Bar (SD500) and Estimation of its Structural Performance under Monotonic Loading, Journal of the Korea Institute for Structural Maintenance Inspection, Vol. 11, No. 6, November 2007, pp.169-180. (in Korean).
6) Kim, H. (2008) Structural Performance of Steel Pipe Splice for SD500 High-strength Reinforcing Bar under Cyclic Loading, Architectural Research, Architectural Institute of Korea, Vol. 10, No. 1, June 2008, pp.13-23.
7) Hayashi, Y., Nakatsuka, T., Miwake, I. and Suzuki, K. (1997) Mechanical Performance of Grout-Filled Coupling Steel Sleeves under Cyclic Loads, Journal of Structural and Construction Engineering, Architectural Institute of Japan, No. 496, June 1997, pp.91-98. (in Japanese).
8) Lee, L., Yi, W. and Lee, Y. (1997) Study on Bar Connection with High Strength Mortar Grout-Filled Steel Pipe, Journal of Architectural Institute of Korea, Vol. 13, No. 8, August 1997, pp.147-154. (in Korean).
9) Lee, Y. and Yi, W. (2004) Experimental Study of Reinforcement Bar Connection using Steel Pipe Sleeve, Journal of Architectural Institute of Korea, Vol. 20, No. 9, September 2004, pp.29-36. (in Japanese).
10) Architectural Institute of Japan. (1990) Design of Reinforced Concrete Structures, Architectural Institute of Japan, March 1990, pp.34-35. (in Japanese).
11) Untrauer, R. E. and Henry, R. L. (1965) Influence of Normal Pressure on Bond Strength, ACI Journal, May 1965, pp.577-585.
12) Ahn, B., Kim, H. and Park, B. (2003) Confining Effect of Mortar Grouted Splice Sleeve on Reinforcing Bar, Journal of the Korea Concrete Institute, Vol. 15, No. 1, February 2003, pp.102-109. (in Korean).