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Estimation of Failure Mode of Mortar-Filled Sleeve Rebar Splices

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Abstract

In order to establish a more rational structural design method for mortar-filled sleeve rebar splices, it is necessary to analyze and evaluate structural factors affecting the structural performance of these rebar splices. It is very desirable to be able to quantitatively estimate the failure mode of the splices at the design stage. A method for estimating the failure mode of mortar-filled sleeve rebar splices presented from the existing research is not clear because the boundary of failure mode is not expressed in formulas. There are also limitations using the methods because the research is based on limited number of test variables, insufficient number of test specimens, and the fact that only steel pipe sleeves were used. Therefore, to establish a more general and comprehensive failure mode estimation method, it needs to be presented in a more quantitative and explicit fashion and evaluated using more diverse variables. In this study, as part of an effort to generate basic data for the establishment of a more rational and quantitative structural design method for mortar-filled sleeve rebar splices, the failure mode estimation method is presented based on the existing bond strength equations of sleeve rebar splices. In addition, to examine the suitability of this failure mode estimation method, the failure modes of 303 sleeve rebar splices were evaluated. The evaluation results indicated that the failure mode estimation method for mortar-filled sleeve rebar splices proposed by this study would yield a failure mode estimation with a sufficiently practical accuracy.

Keywords: failure mode, mortar-filled sleeve splice, bond failure, bar fracture

1 Introduction

Since mortar-filled sleeve rebar splices have excellent workability, minimize the number of on-site workers, and secure stable quality, they are continuously being used as the rebar splice method for reinforced concrete structures and precast concrete structures. It is very important to establish a more rational and quantitative structural design method for the sleeve rebar splices in order to ensure the appropriate design of the structure in which the rebar splices are used. For this, analysis and evaluation of structural factors affecting the structural performance of mortar-filled sleeve reinforcement splices are required, and it is desirable to be able to quantitatively estimate the failure modes that can occur in sleeve reinforcement splices at the design stage.

However, so far, there have been few studies on the method of estimating the failure mode of mortar-filled sleeve rebar splices. Among them, Hayashi et al., (1994, 1997) produced steel pipe sleeve rebar splice specimens using the strength of grout, the development length of rebar, and the size of rebar as variables, and executed monotonic and cyclic loading tests to evaluate the structural performance of the specimens. From the results of this experimental study, the method for evaluating the bond strength between the rebar embedded in the sleeve and the filled mortar and the concept of the failure mode estimation using the proposed bond equations were presented. However, the failure mode estimation method proposed by Hayashi et al. (1994) is somewhat unclear because the boundary of failure mode is not expressed in

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specific formulas. To verify the method of estimating the failure mode 20 experimental results that Hayashi's team produced were used. It was reported that the method of estimating the failure mode responded well to the experimental results. However, the verification process is insufficient because it is based on limited number of test variables, insufficient number of specimens, and the fact that only steel pipe sleeves were used. Therefore, to establish a more general and comprehensive method of estimating the failure mode of mortar-filled sleeve reinforcement splices, it needs to be presented in a more quantitative and explicit fashion and evaluated using more diverse variables.

In this study, in order to make basic data for the establishment of a more rational and quantitative structural design method for mortar-filled sleeve rebar splices, the failure mode estimation method for mortar-filled sleeve rebar splices is derived and the estimation method is verified using the existing 303 test results of the mortar-filled sleeve rebar splices.

2 Analytical Experiment Data

In this study, 303 test specimens were selected to verify the failure mode estimation method of mortar-filled sleeve rebar splices. The data of the test specimens are shown in Table 1. The specimens selected here failed in either bar fracture or bond failure. In particular, the specimens with bond failure were divided into two cases where bond failure occurred before the embedded rebar yielded, and the failure occurred after the embedded rebar yielded. Here, in case of the bond failure after the yielding of embedded rebars, it was further subdivided based on the maximum strength of test specimens listed as follows: (a) greater than or equal to the average tensile strength of the rebar (σ_{ua}), (b) less than the average tensile strength of the rebar (σ_{ua}), but greater than the lower limit of tensile strength of the rebar (σ_{ul}), and (c) less than the lower limit of tensile strength of the rebar (σ_{ul}), but higher than the average yield strength of the rebar (σ_{ya}). Table 2 shows the statistical data on the tensile strength and yield strength of rebars obtained from the tensile strength material test results of rebars used in the specimens to be analyzed in this study. The specimens of this study were carried out by 6 research groups, with two types of sleeves, cast type and steel pipe type, and two types of rebars embedded in the sleeves, SD400 and SD500. In addition, the development length of rebars of 2 ~ 10D (D is the nominal diameter of rebars), the compressive strength of filling mortar of 45 ~ 129 MPa, the size of rebars of 9 sizes, D19, D25, D32, D35, D38, D41, and etc., and the two types of loading method, monotonic and cyclic loading, were used for the tests. The sleeve rebar splice experiments conducted by 6 research groups, the subject of this study, were briefly introduced as follows.

2.1 Experiment of Japan Splice Sleeve Company

Japan Splice Sleeve Company (1992, 1993) conducted monotonic and cyclic loading tests to verify the structural performance of sleeve rebar splices developed using spheroidal graphite cast iron and reported the results. The variables of this experiment were the development length of rebars, the compressive strength of filling mortar, and the size of rebars. Here, the sleeve has inner protrusions parallel to the circumferential direction, and the narrow inlet side of the sleeve has a shape in which the diameter of the sleeve decreases from the center of the sleeve to the inlet side, but the wide inlet side of the sleeve has a constant outer diameter.

2.2 Experiment of Asse et al.

In 1996, Asse et al. (1996) conducted cyclic loading tests on cast type sleeve rebar splices, where the main experimental variables were the compressive strength of filling mortar and the size of the reinforcing bars and published the study results. This experimental study was conducted to examine the application of SD500 rebars, which have higher strength than SD400, on newly developed mortar-filled sleeve rebar splices.

2.3 Experiment of the Author et al. of this Study

In 1998, after developing the sleeves using spheroidal graphite cast iron, GCD500, the author conducted monotonic and cyclic loading tests several times to evaluate the overall structural performance such as tensile strength and rigidity of the sleeve rebar splices with embedded rebars, SD400, and published the research results (Kim, 2004, Samsung Engineering & Construction et al., 1998). The main variables of this experiment were the final failure modes, the development length of rebars, the compressive strength of filling mortar, and the size of rebars. Since 2008, after the development of steel pipe sleeves for SD500 rebars, the results of monotonic and cyclic loading tests to evaluate the structural performance of the sleeve splices were reported (Kim, 2008a, 2012). The main variables of these experiments were the development length of rebars, the size of rebars, and the loading methods. Also, in 2008, after developing the cast type sleeves using spheroidal graphite cast iron, GCD600, for SD500 rebars, experiments were conducted to evaluate the structural performance of the sleeve splices and the research results were published (Park et al., 2008; Kim, 2008b). The main variables of the experiments were the development length of rebars, the compressive strength of mortar, the size of rebars, and the loading methods. Meanwhile, Kim et al. (Kim & Lee, 2012; Kim, 2008c) calculated the confining force acting on mortar-filled reinforcing bar splices by analyzing the strain measured on the surface of the sleeve to investigate the restraint effect of the mortar-filled reinforcing bar splices. Fig. 1 shows a typical cast type sleeve cross-section used in the sleeve rebar splice tests conducted by the author. Fig. 2 shows the specimen in which the reinforcing bar was fractured and the specimen of bond failure, respectively, from the mortar-filled sleeve reinforcing bar splice experiments.

2.4 Experiment of Hayashi et al.

In 1994, after developing a steel pipe sleeve rebar splice that has internal protrusions, Hayashi and his team (Hayashi et al., 1994, 1997) conducted experiments to determine the structural performance such as tensile strength along with the bond characteristics between the embedded bar and filled mortar and presented their experiment results. The main test variables of this study were the development length of reinforcing bars, the compressive strength of filled mortar, and the loading methods.

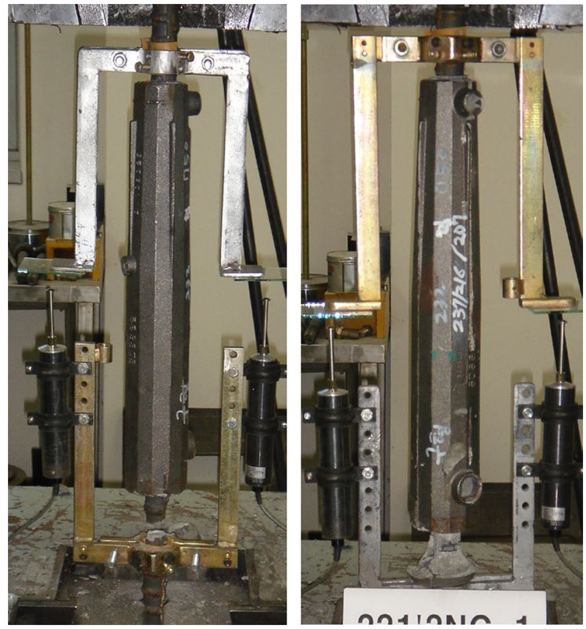

Fig. 2 Final failure pattern. (Bar fracture and bond failure)

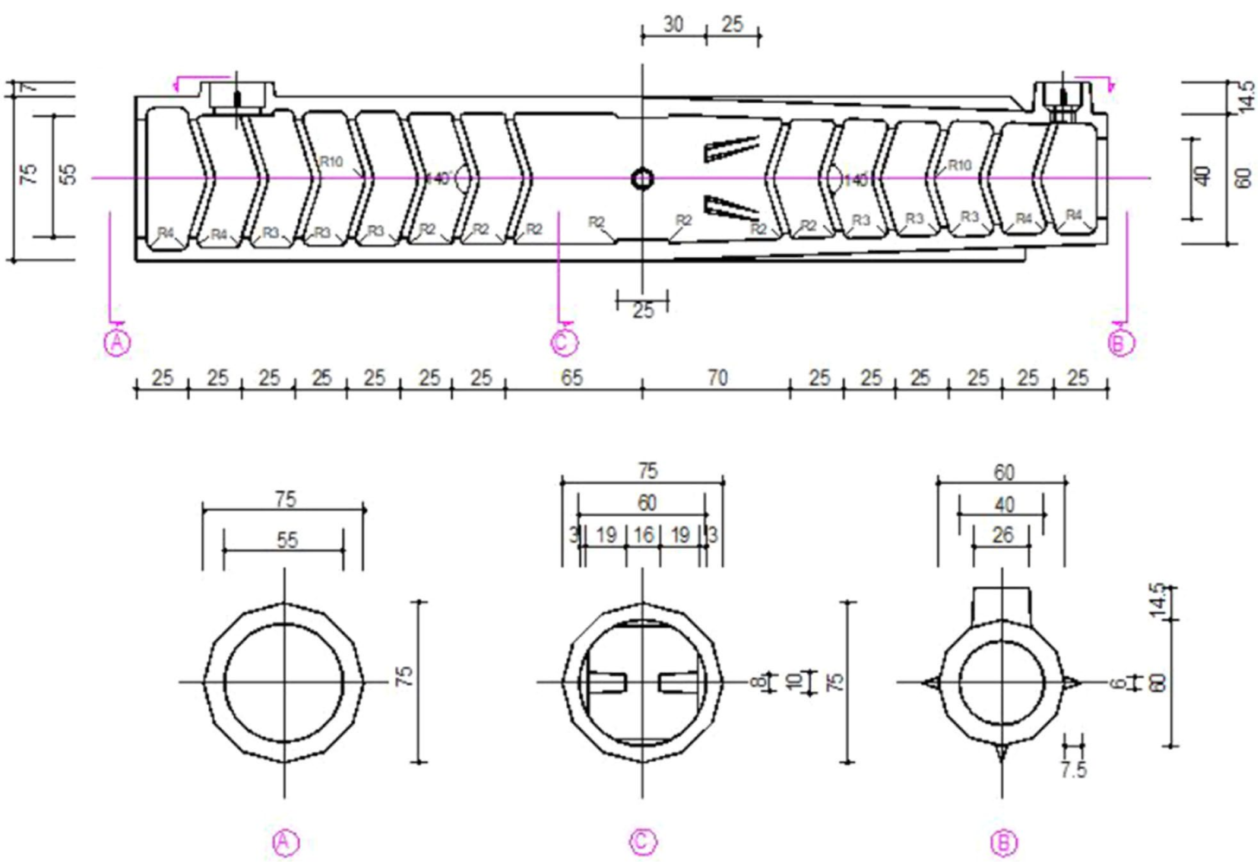

Fig. 1 Details of cast type splice

2.5 Experiment of Lee et al.

In 1997, Lee et al. (1997a; b) developed several shapes of steel pipe sleeves using steel pipes for pressure piping, and afterwards conducted several experiments by applying monotonic loading on rebar splices and reported the results. The main test variables of this study were the shape of steel pipe sleeves.

2.6 Experiment of Einea et al.

In 1995, after Einea et al. (1995) developed steel pipe sleeves that had different steel pipe sleeve shapes, Einea and his colleagues conducted monotonic loading experiments to evaluate the structural performance such as the tensile strength of steel pipe sleeve rebar splices and the confining effect of the sleeves and reported their test results. The main variables of their experiments were the shape of sleeves, the development length of rebars, and the compressive strength of mortar.

2.7 Other Experiments

Lin and Wu (2016) evaluated the structural performance of mortar-filled reinforcing bar splices with SD500 and SD600 rebars by conducting monotonic and cyclic loading tests. In particular, stress and strain relationship of mortar-filled reinforcing bar splices subjected to monotonic and cyclic loading was presented. Henin et al. (2015) evaluated the structural performance of the mortar-filled steel pipe type reinforcing bar splices with SD400 rebar embedded in it through the experiments and analysis and presented the coefficient of friction between the reinforcing bar and the mortar. Ling et al. (2016) evaluated the structural performance of two types of steel pipe sleeve rebar splices through the experiments and analysis. In addition, Zheng et al. (2016) confirmed the structural performance and failure mode of mortar-filled steel pipe type reinforcing bar splices in which SD400 rebars were embedded through the experiments and analysis and proposed the bond strength formula considering the confining force acting on rebar splices.

3 Estimation Method for Failure Mode and Review

3.1 Estimation Method for Failure Mode

After Hayashi's research group (Hayashi et al., 1994) conducted the structural performance tests of mortar-filled steel pipe sleeve rebars and analyzed the results, they classified the test specimens into two cases: the embedded rebar in the sleeve yielding and the embedded rebar in the sleeve not yielding and proposed the equations of the bond strength of sleeve rebar splices (Hereinafter, Hayashi equations). Here, the maximum strength of the rebar splice with the development length (L_y) capable of supporting the yield strength (P_y) of the embedded rebar in the sleeve is expressed as Eq. 1, where the distribution of the bond stress between the rebar and the mortar is divided into two terms: the area where the rebar yields and the area where the rebar does not yield. On the other hand, in case of bond failure in which the rebar is separated from the filling mortar before the yielding of the embedded rebar occurs, the bond strength is expressed as Eq. 2. Here, the symbols in Eqs. 1 and 2 are represented by Eqs. 3, 4, 5, 6.

$$p_{sy} = \tau_{by} \cdot \pi \cdot D \cdot (L - L_y - l) + \tau_{bm} \cdot \pi \cdot D \cdot L_y \quad (1)$$

$$p_{sb} = \tau_{bm} \cdot \pi \cdot D \cdot (L - l) \quad (2)$$

$$\tau_{by} = 0.3 f_g \quad (3)$$

$$\tau_{bm} = 0.5 f_g \quad (4)$$

$$L_y = P_y / (\tau_{bm} \cdot \pi \cdot D) \quad (5)$$

$$l = 0.7D \quad (6)$$

where, D: diameter of rebar, L: development length of rebar, P_y: yield strength of rebar, f_g: compressive strength of grout.

Meanwhile, the author conducted mortar-filled sleeve rebar splice experiments with a strain gauge attached to the surface of the rebar embedded in the sleeve and analyzed the distribution of the bond stress generated between the rebar and the filled mortar. By regarding the bond strength of the sleeve rebar splice based on the two cases where the embedded rebar yielded and the embedded rebar did not yield, the author proposed the equations (Hereinafter, Kim equations) by modifying Hayashi equations as follows (Kim, 2010). The symbols used in Kim equations are the same as those of the Hayashi equations.

$$\tau_{by} = 0.25 f_g \quad (7)$$

$$L_y = 0.9 P_y / (\tau_{bm} \cdot \pi \cdot D) \quad (8)$$

$$l = 0.5D \quad (9)$$

The failure modes in mortar-filled sleeve rebars can be divided into the following cases: (a) the bond failure before the embedded rebar yields, (b) the bond failure after the embedded rebar yields, and (c) the tensile failure of the embedded rebar. In the paper of Hayashi et al. (1994), the failure modes in the above three cases were expressed by the following equations.

$$P_{sb} < P_y \quad (10)$$

$$P_y \leq P_{sy} < P_u \tag{11}$$

$$P_u \leq P_{sy} \tag{12}$$

where, P_u: tensile strength of embedded rebar.

In a mortar-filled sleeve reinforcing bar splice, the boundary between the bond failure before the embedded reinforcing bar yields and the bond failure after the reinforcing bar yields represents the case where the bond strength (P_{sb}) based on the bond failure before the yielding of the rebar and the yield strength (P_y) of the rebar embedded in the sleeve are equal. In addition, the boundary between the bond failure after the rebar embedded in the sleeve yields and the tensile fracture of the rebar at the sleeve rebar splice represents the case where the bond strength (P_{sy}) based on the bond failure after the yielding of rebar and the tensile strength (P_u) of the embedded rebar in the sleeve are equal. The two boundaries of different failure zones can be obtained using the above equations.

Based on Hayashi equation, the two boundaries described above are derived using the relationship between the ratio of the development length to the diameter of the embedded rebar (L/D) and the compressive strength of filled mortar (f_g), and the relationships are derived as follows.

$$\frac{L}{D} = \frac{\sigma_y}{2f_g} + 0.7 \tag{13}$$

$$\frac{L}{D} = \frac{(5\,\sigma_u - 2\,\sigma_y)}{6f_g} + 0.7 \tag{14}$$

where, σ_y: yield strength of rebar, σ_u: tensile strength of rebar.

Additionally, by using the method similar to Hayashi equation the above boundaries based on Kim equation can be derived as follows.

$$\frac{L}{D} = \frac{1.1\sigma_y}{2f_g} + 0.5 \tag{15}$$

$$\frac{L}{D} = \frac{(2\,\sigma_u - 0.9\,\sigma_y)}{2f_g} + 0.5 \tag{16}$$

3.2 Review of Failure Mode Estimation Method

Figs. 3, 4, 5, 6 show the failure zones of mortar-filled sleeve rebar splices obtained by the method described above. Here, the yield strength and tensile strength of the rebar embedded in the sleeve were obtained from the material test results of rebars shown in Table 2. Also, along with the failure zones obtained from the two methods presented above, these figures show the failure modes of each experiment result by classifying them into two cases: when embedded bar is SD400 and when embedded bar is SD500. In addition, the experimental results shown in Figs. 3, 4, 5, 6 were compared by classifying the sleeves into cast type and steel pipe type, and the failure mode was divided into the specimen with the fractured rebar and the specimen with bond failure. Here,

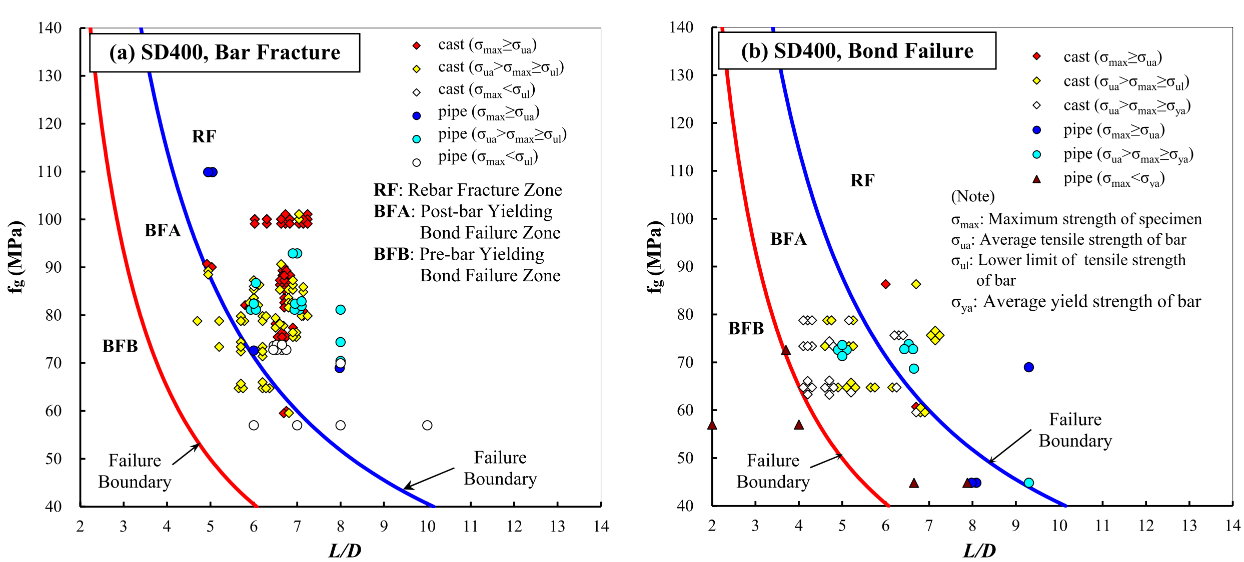

Fig. 3 Failure mode estimation based on Hayashi equation. (Test specimens with SD400)

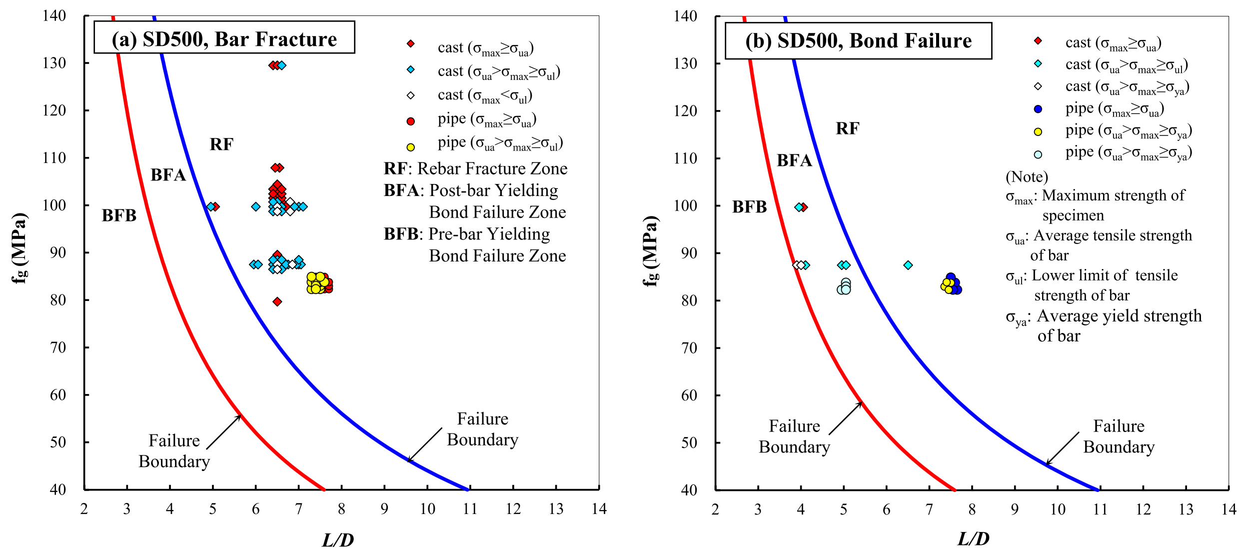

Fig. 4 Failure mode estimation based on Hayashi equation. (Test specimens with SD500)

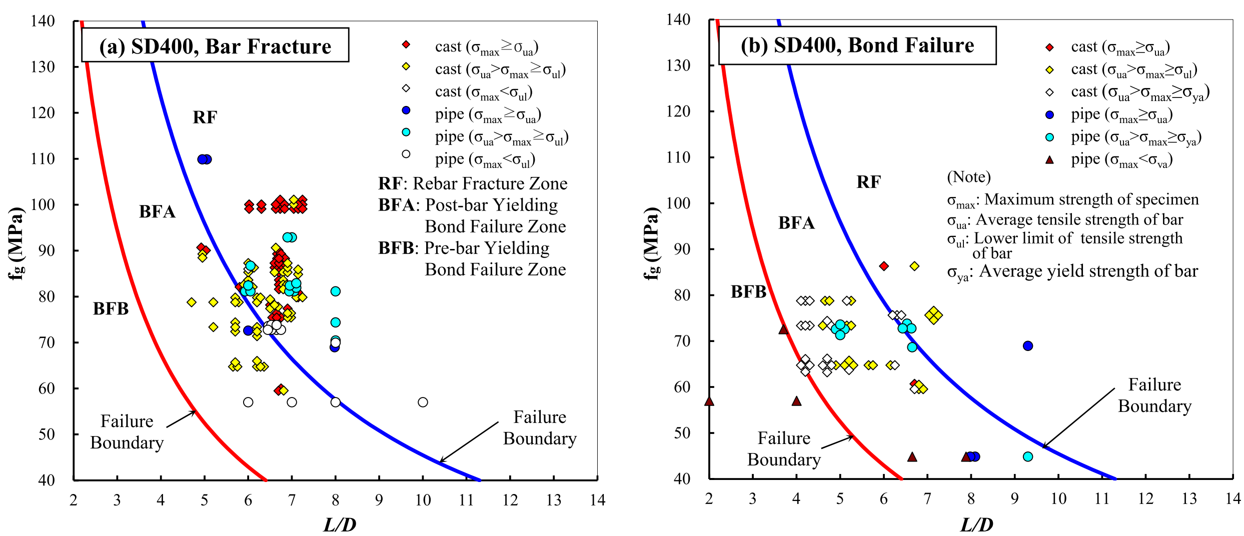

Fig. 5 Failure mode estimation based on Kim equation. (Test specimens with SD400)

the specimen in which the reinforcing bar was fractured was classified and displayed according to the maximum strength of the specimen. The specimen with bond failure was classified into two cases where the reinforcing bar was separated from the filling mortar before the embedded rebar yielded, and the rebar was separated from the mortar after the rebar yielded. Among them, in case of the bond failure after the yielding of embedded rebars, as mentioned earlier in this paper, it was further subdivided based on the maximum strength of test specimens listed as follows: (a) greater than or equal to the average tensile strength of the rebar (σ_{ua}), (b) less than the average tensile strength of the rebar (σ_{ua}), but greater than the lower limit of tensile strength of the rebar (σ_{ul}), and (c) less than the lower limit of tensile strength of the rebar (σ_{ul}), but higher than the average yield strength of the rebar (σ_{ya}). Here, the values shown in Table 2 were used for the average tensile strength of the rebar (σ_{ua}), the lower limit of tensile strength of the rebar (σ_{ul}), and the average yield strength of the rebar (σ_{ya}).

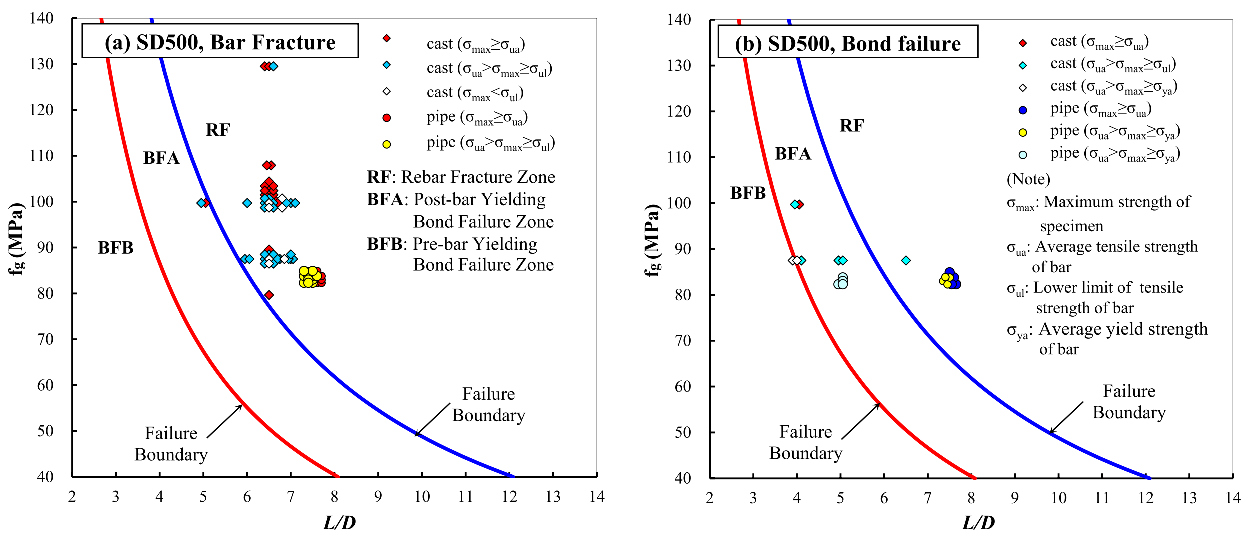

Fig. 6 Failure mode estimation based on Kim equation. (Test specimens with SD500)

In Figs. 3 and 4, the failure zones obtained by Hayashi equation are expressed along with the failure modes of the experimental results. As shown in Fig. 3a, among 146 test specimens with SD400 rebars that failed in the fracture of rebars, 126 specimens were included in the reinforcing bar fracture zone according to Hayashi equation, so 86% of the specimens were consistent with the test results. In addition, the effect of the type of sleeve, that is, the difference between the cast type sleeve and the steel pipe type sleeve, was not particularly shown here. As shown in Fig. 3b, among 66 specimens with SD400 rebars that failed in bond, 48 specimens calculated by the Hayashi equation were consistent with the experimental results, showing a failure mode agreement of 73%. Here, among five specimens where bond failure occurred before the reinforcing bars yielded, the failure modes of three specimens were not consistent with the test results. In particular, such results were evident when the filling mortar compressive strength of the specimens was less than 50 MPa. On the other hand, as shown in Fig. 4a, all 71 specimens using SD500 reinforcing bars that failed in the fracture of rebars ended up in the rebar fracture zone according to Hayashi formula. As shown in Fig. 4b, among 20 specimens with SD500 rebars that failed in bond, 11 specimens calculated by Hayashi equation were consistent with the experimental results, showing a failure mode agreement of 55%.

In Figs. 5 and 6, the failure zones obtained by Kim equation are expressed along with the failure modes of the experimental results. As shown in Fig. 5a, among 146 test specimens with SD400 rebars that failed in the fracture of rebars, 116 specimens were included in the reinforcing bar fracture zone according to Kim equation, so 79% of the specimens were consistent with the test results. As shown in Fig. 5b, among 66 specimens with SD400 rebars that failed in bond, 51 specimens calculated by the Kim equation were consistent with the experimental results, showing a failure mode agreement of 77%. Here, among five specimens where bond failure occurred before the reinforcing bar yielded, the failure modes of three specimens were consistent with the test results. Although two specimens were failed to match the test results, compared to the results based on Hayashi equation, the results based on Kim equation were closer to the boundary between the bond failure before the rebar yielded and the bond failure after the rebar yielded. On the other hand, as shown in Fig. 6a, among 71 specimens using SD500 rebars that failed in the fracture of rebars, 69 specimens were included in the rebar fracture zone according to Kim equation, so 97% of the specimens were consistent with the test results. As shown in Fig. 6b, among 20 specimens with SD500 rebars that failed in bond, 11 specimens calculated by the Kim equation were consistent with the test results, showing a failure mode agreement of 55%, and the failure mode was estimated with an accuracy similar to the case by Hayashi equation. The failure mode estimation results for 303 specimens were shown in Fig. 7. When looking at all the specimens analyzed in this study, for the specimens failed in the fracture of rebars Hayashi equation estimated the failure mode 6% more accurately than Kim equation, but for the specimens with bond failure Kim equation predicted the failure mode 4% more accurately than Hayashi equation. For all specimens including all failure modes, Hayashi's

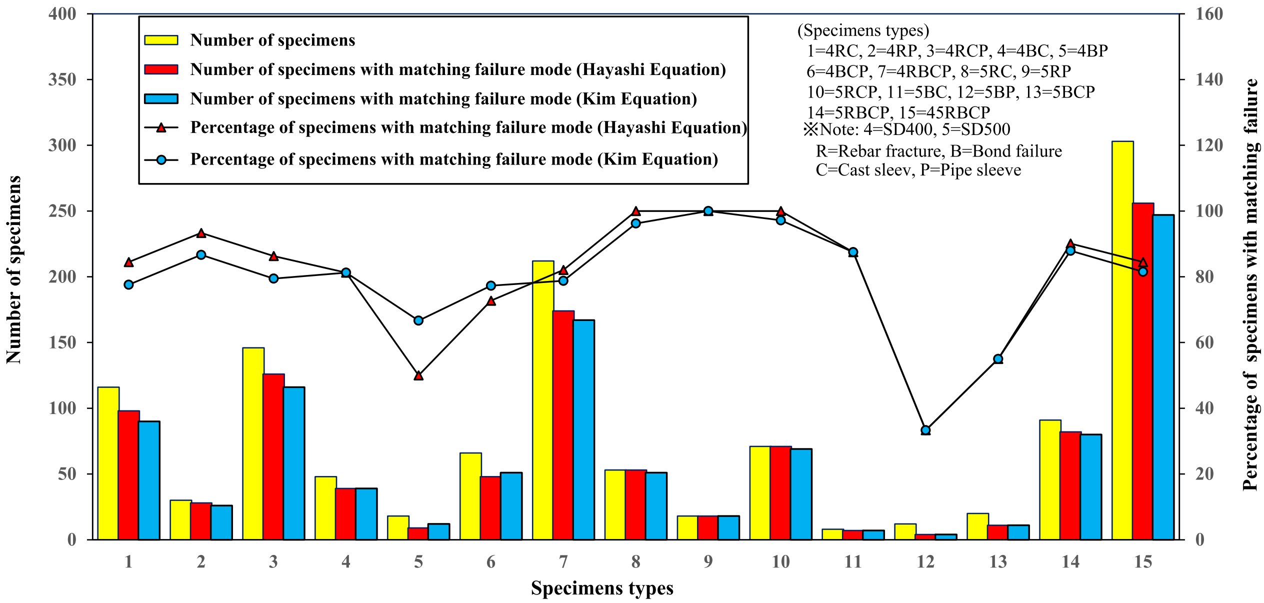

Fig. 7 Analysis of failure mode estimation results

method estimated the failure mode about 2% more accurately than Kim's method.

On the other hand, Fig. 8 shows the effect of the shape of the sleeve on the estimation of the failure mode of the mortar-filled sleeve rebar splices. Here, the failure zone calculated by Hayashi equation is shown for the specimen with SD400 rebars embedded in the sleeve. By referring to the previous research (Kim, 2004), the shape of the sleeve was determined by selecting the ratio of the thickness of the sleeve to the inside diameter of the sleeve (t/d_i) and the ratio of the inside diameter of the sleeve wide opening to the nominal diameter of the embedded rebar ($_e d_i/d$). The test specimens were classified based on t/d_i and $_e d_i/d$ values of 0.1 and 2, respectively. As shown in Fig. 8a, in case of the specimens in which the reinforcing bar was fractured, there were 20 specimens not included in the rebar fracture zone based on Hayashi equation, and 18 of them had the sleeve shape of

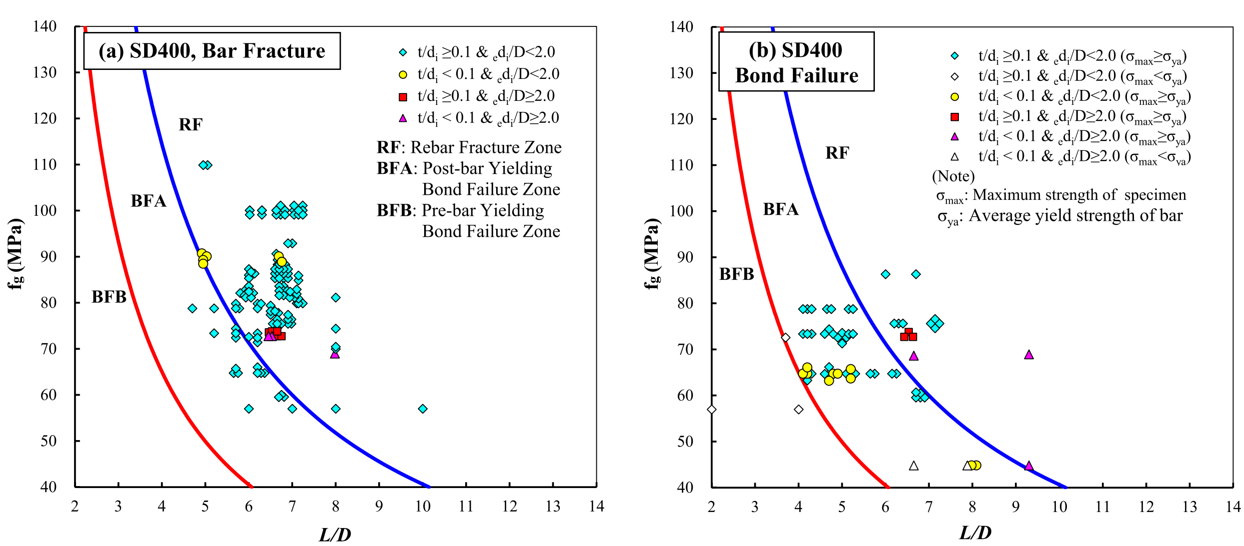

Fig. 8 Effect of sleeve shape for failure mode estimation based on Hayashi equation. (Test specimens with SD400)

Table 1 Overview of experimental data

Representative researcher	Year of study	Number of test specimens	Sleeve type	Bar kind	Final failure mode*1	L*2(D)	f_m*3 (MPa)	Bar size*4	Loading method*5
Splice Sleeve Company	1992 1993	52	Cast	SD400	RF(45) BFAa(3) BFAb(4)	4.9–7.1	76–100	D22(5), D25(4) D29(2), D32(1) D35(15), 38(2) D41(23)	M(33) C(19)
Asse	1996	17	Cast	SD500	RF(17)	6.5	80–129	D16(2), D19(3) D22(2), D25(2) D29(2), D32(2) D35(1), D38(2) D41(1)	C(17)
Author	1998	42	Cast	SD400	RF(35) BFAa(1) BFAb(4) BFAc(2)	6.0–6.8	60–86	D19(22) D38(20)	M(21) C(21)
	1998	14	Cast	SD400	RF(14)	6.5–6.8	75–78	D19(6), D25(1), D32(1), D38(6)	M(6) C(8)
	2001	56	Cast	SD400	RF(22) BFAa(21) BFAb(13)	4.2–6.2	65–79	D19(13) D25(43)	M(56)
	2008	44	Cast	SD500	RF(36), BFAa(2) BFAb(5), BFAc(1)	4.0–7.0	88–100	D25(8), D32(13) D35(23)	M(25) C(19)
Hayashi	1994	21	Pipe	SD400	RF(19), BFB(2)	2.0–10.0	57–93	D35(21)	M(21)
	1996	9	Pipe	SD400	RF(3), BFB(1) BFAa(5)	3.7–6.0	73–110	D35(9)	M(2) C(7)
Lee	1994	2	Pipe	SD400	RF(2)	6.5	73	D22(2)	M(2)
	1996	8	Pipe	SD400	RF(5), BFAa(3)	6.5	73	D22(8)	M(8)
Einea	1995	8	Pipe	SD400	RF(1), BFB(2) BFAa(2) BFAc(3)	6.7–9.3	45–69	D16(1) D19(7)	M(8)
Author	2007 2008	30	Pipe	SD500	RF(18), BFAa(4) BFAb(4) BFAc(4)	5.0–7.5	82–84	D19(4), D25(5) D32(13), D35(8)	M(16) C(14)
Total*6	1992–2008	303	Cast (225) Pipe (78)	SD400 (212) SD500 (91)	RF(217), BFB(5) BFAa(41) BFAb(30) BFAc(10)	2.0–10.0	45–129	D16(3), 19(55) D22(17),D25(63) D29(4), D32(30) D35(77),D38(30) D41(24)	M(198) C(105)

*1,*4,*5,*6 : The numbers in ( ) represent the corresponding number of test specimens

*1 *RF*: Reinforcing bar fracture, *BFB*: Bond failure of bar separating from filled mortar before the bar yields, *BFAa*: Bond failure of bar separating from filled mortar after the bar yields($\sigma_{ul} > \sigma_{max} \geq \sigma_{ya}$), *BFAb*: Bond failure of bar separating from filled mortar after the bar yields($\sigma_{ua} > \sigma_{max} \geq \sigma_{ul}$), *BFAc*: Bond failure of bar separating from filled mortar after the bar yields($\sigma_{max} \geq \sigma_{ua}$)

*2 The development lengths of reinforcing bar is represented as a multiple of the nominal diameter of bar

*3 Compressive strength of filled mortar

*5 *M*: Monotonic loading, *C*: Cyclic loading

$t/d_i \geq 0.1$ and ${}_ed_i/d < 2$, and for the other two specimens, the shape of the sleeve was $t/d_i < 0.1$ and ${}_ed_i/d < 2$. Since these 20 specimens had the shape of the sleeve that was relatively advantageous for its confining effect, it was considered that increase of the bond strength between the embedded rebar in the sleeve and the filling mortar led to the failure of the reinforcing bars prior to the bond failure. As shown in Fig. 8b, in case of the specimens in which bond failure occurred, for 8 specimens relatively difficult to exert the confining effect due to the shape of the sleeve end of ${}_ed_i/d \geq 2$, all specimens were found to be inconsistent with the failure zones estimated based on Hayashi equation. From the above results, it was found that the shape of the sleeve affected the confining effect of the sleeve, and this also affected the bonding strength between the embedded reinforcing bar and the filling mortar in the sleeve.

As shown in the above results, it was found that the failure mode of the mortar-filled sleeve reinforcing bar splice could be estimated with sufficiently practical accuracy using the existing bond strength formula. In the future, in the structural design of mortar-filled sleeve reinforcing bar splices, a rational and quantitative structural design of sleeve rebar splices appears to be possible by using the failure mode estimation method.

Table 2 Statistical data for the tensile strength and yield strength of bar

Bars	Mechanical properties	Statistical items[*1]	Statistics [*2]
SD400	Yield strength	Average (σ_{ya})	429.3 MPa (1.094f_y)
		Upper limit (σ_{yu})	477.0 MPa (1.216f_y)
		Lower limit (σ_{yl})	381.6 MPa (0.972f_y)
		Standard deviation	24.3 MPa (0.062f_y)
	Tensile strength	Average (σ_{ua})	625.1 MPa (1.593f_y)
		Upper limit (σ_{uu})	683.5 MPa (1.742f_y)
		Lower limit (σ_{ul})	566.6 MPa (1.444f_y)
		Standard deviation	29.8 MPa (0.076f_y)
SD500	Yield strength	Average (σ_{ya})	551.3 MPa (1.124f_y)
		Upper limit (σ_{yu})	584.0 MPa (1.191f_y)
		Lower limit (σ_{yl})	518.6 MPa (1.057f_y)
		Standard deviation	16.6 MPa (0.034f_y)
	Tensile strength	Average (σ_{ua})	711.7 MPa (1.451f_y)
		Upper limit (σ_{uu})	772.3 MPa (1.574f_y)
		Lower limit (σ_{ul})	651.1 MPa (1.328f_y)
		Standard deviation	30.8 MPa (0.063f_y)

[*1] Upper limit and lower limit are based on a 95% confidence interval

[*2] f_y: Specified yield strength of bar

4 Conclusions

In this study, as part of an effort to generate basic data for the establishment of a more rational and quantitative structural design method for mortar-filled sleeve reinforcement splices, the failure mode estimation method of mortar-filled sleeve rebar splices that utilizes the formulas proposed for the evaluation of the bond strength of sleeve rebar splices is presented. To examine the suitability of the failure mode estimation method, the failure modes of 303 sleeve rebar splices were investigated and the following conclusions were obtained.

(1) Using the failure mode prediction model for mortar-filled sleeve rebar splices presented in this study, it was found that the failure mode of sleeve rebar splices could be estimated with sufficiently practical accuracy.

(2) In the estimation of the failure mode of mortar-filled sleeve reinforcing bar splices calculated by the formula previously proposed for the evaluation of the bond strength of mortar-filled sleeve reinforcing bars, Hayashi equation generates better failure mode estimations when the specimen failed in the fracture of rebar, and Kim equation generates better results when the specimen failed in bond.

(3) For the estimation of the failure mode of mortar-filled sleeve reinforcing bar splices, the type of sleeve, such as cast type and steel pipe type, had little effect on the results.

(4) For the estimation of the failure mode of mortar-filled sleeve reinforcing bar splices, the specimens that had the shape of sleeve that was advantageous for its confining effect failed in rebar fracture, while the specimens relatively difficult to exert the confining effect failed in bond.

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HKK conceptualization, investigation, analyzing data, writing the manuscript. MSL investigation, analyzing data, writing and editing the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interest.

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