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공학석사학위논문

Bond Behavior between Concrete and Reinforcing Steel Subjected to Extreme Loadings

극한 하중 상황에서의
철근 콘크리트 부착 거동

2021 년 2 월

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이 논문을 공학석사 학위논문으로 제출함
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ABSTRACT

Bond Behavior between Concrete and Reinforcing Steel Subjected to Extreme Loadings

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As concrete structures these days are being designed with bigger scale compared to ones in the past, the potential risks with extreme loadings are getting larger. Extreme loadings like collision of car, ship, and aircraft, explosion, earthquake, tsunami, etc. are applying high deformation rate than that under quasi-static state, so-called dynamic loadings. Especially, for reinforced concrete structures like bridge or pylon, those dynamic loadings are applied mostly under the bottom part of structures in high possibility. And, since the material properties such as concrete and reinforcing steel are changed, bond behavior between them should be investigated.

In the bottom part of them, there is joint part between columns and foundations, so basically it could be said these parts are comparatively weak part in the whole structure. So, to remove this flaw the concrete structure is being designed with the development length. In the design equations of development length in ACI 318 and Eurocode 2, numerator and denominator

imply rebar yield strength and concrete bond strength, respectively. At this moment, when we consider dynamic effect on each term, rebar yield strength and concrete bond strength, if the DIF_b is smaller than DIF_s, it means that it requires longer development length in dynamic loadings than one in static loadings. However, currently no design codes and guidelines are considering dynamic effect on development length design or concrete bond strength, and no proper bond DIF is found in previous studies. Moreover, in previous dynamic pull-out test, the amount of test data with specimens showing pull-out failure is short. Therefore, this study focuses on that once the bond DIF is obtained with static and dynamic pull-out test showing pull-out failure mode, the safety of the current development length design method is investigated with comparing to DIF for rebar yield strength.

After the specimen dimension showing pull-out failure mode is decided in preliminary test, the main pull-out test is being performed with same experimental method. With the data of rebar tensile test and strain gauge, bond strength is calculated. Strain rate is also read with slope between moments when the strain is zero and maximum in strain gauge data. At the result, bond DIF is being generated with ratio bond strength in dynamic test to one in static test along the strain rate. Malvar DIF_s was used to compare with bond DIF from this study, and it is found that on the strain rate in currently tested range, the bond DIF is bigger than rebar yield strength DIF, which means no dynamic effect need to be considered in development length design.

The conclusion above is only valid in the test performed range. So, it could be said that the dynamic effect does not need to be considered where the rebar strain rate is smaller than $5s^{-1}$, concrete compressive strength is smaller than

25MPa, and the reinforcing steel yield strength is bigger than 400MPa. However, it should be verified in concrete with higher compressive strength because the bond DIF would be affected with it.

Keywords: pull-out test, development length, bond strength, dynamic increase factor, strain rate

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NOTATIONS

Symbol		Definition and description
A_s	=	Nominal area of rebar
l_d	=	Development length
l_{dd}	=	Development length in dynamic state
DIF	=	Dynamic increase factor
DIF_S	=	DIF of rebar yield strength
DIF_u	=	DIF of rebar ultimate strength
DIF_b	=	DIF of bond strength
E	=	Young's modulus of specimen
d_b	=	Diameter of specimen
f_c'	=	Compressive strength of concrete
f_y	=	Rebar yield strength
t	=	Time
t_1	=	Time when strain is zero
t_2	=	Time when strain is maximum
ε	=	Strain
ε_y		Rebar yield strain
ε_1	=	Zero strain

ε_2	=	Maximum strain
$\dot{\varepsilon}$	=	Strain rate
ψ_t	=	Reinforcement location factor
ψ_e	=	Reinforcement coating factor
ψ_s	=	Reinforcement size factor
ψ_g	=	Reinforcement grade factor
c_b	=	Concrete cover thickness
K_{tr}	=	Confining reinforcement contribution factor
α_1	=	Effect of rebar assuming adequate cover
α_2	=	Effect of concrete minimum cover
α_3	=	Effect of confinement by transverse reinforcement
α_4	=	Effect of welded transverse bars
α_5	=	Effect of pressure transverse
f_{bd}	=	Bond strength
l_b	=	Bond length
B	=	Specimen width
τ	=	Bond stress

1. Introduction

1.1. Research Background

As the scale of concrete structure is getting bigger recently, the potential risk to be exposed by extreme loadings under them is larger compared to ones in the past. Extreme loadings, so-called dynamic loadings, transfer higher deformation rate than quasi-static state such as collision of car, ship, and aircraft, explosion, earthquake, tsunami, etc. Especially, when the loadings with collisions by car or ship are applied into reinforced concrete structure like bridge or pylon, the bottom part of them would be affected a lot than other parts in most cases.

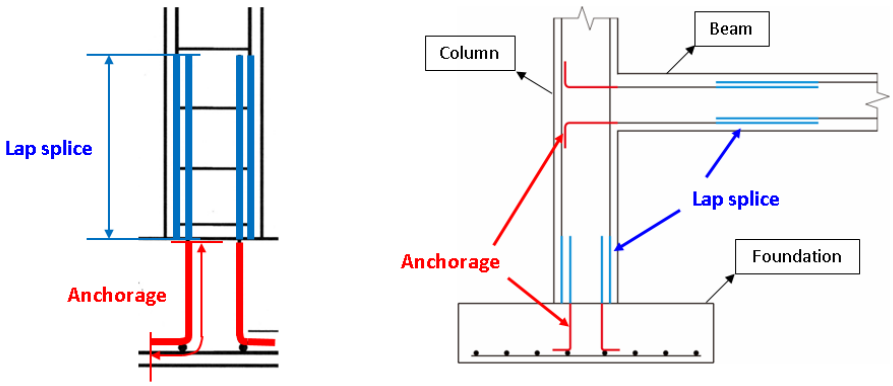


Figure 1.1 Development length in concrete structure

Those bottom parts of concrete structure are made up with joints parts, which are column and foundation, so they are comparatively weak parts in the whole structure. So, as shown in figure 1.1, for supplement of this flaw,

reinforcing steel anchorage and lap splice are designed between them. Other parts designed with same method in the concrete structure are followed; joint part between column and beam, lap splice in the beam.

Table 1.1 Development length design method (Metric unit)

	ACI 318-19	Eurocode 2
Anchorage (hook)	$\left(\frac{f_y \psi_e \psi_r \psi_o \psi_c}{23\lambda\sqrt{f'_c}}\right) d_b^{1.5}$	$\alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 l_{b,rqd}$
Lap splice	nl_d	$\alpha_1\alpha_2\alpha_3\alpha_5\alpha_6 l_{b,rqd}$
Common	$l_d = \left(\frac{f_y}{1.1\lambda\sqrt{f'_c}} \frac{\psi_t \psi_e \psi_s \psi_g}{\left(\frac{c_b + K_{tr}}{d_b}\right)}\right) d_b$	$l_{b,rqd} = \frac{\phi}{4}\frac{f_y}{f_{bd}}$

Design equations for reinforcing steel anchorage and lap slice from ACI 318 and Eurocode 2 are shown above in table 1.1. And, the basic equations for them, the development length design equation, are shown in table 1.1. In these equations, f'_c and f_{bd} are terms for concrete bond strength in static state, and f_y is for generated strength of reinforcing steel when it fails in static state as well. In other words, numerator and denominator in development length equations impose rebar yield strength and concrete bond strength, respectively.

However, as the material properties of concrete and reinforcing steel would be changed in dynamic loading circumstances, bond behavior between

them and development length design method should be investigated in those situations.

$$l_{dd} = \left(\frac{DIF_s}{DIF_b} \right) l_d \tag{1.1}$$

$$l_{dd} = \left(\frac{DIF_s f_y}{1.1\lambda DIF_b \sqrt{f'_c}} \frac{\psi_t \psi_e \psi_s \psi_g}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b \tag{1.2}$$

$$l_{b,rqd} = \frac{\phi}{4} \frac{DIF_s}{DIF_b} \frac{f_y}{f_{bd}} \tag{1.3}$$

If the dynamic increase factor, DIF, is considered in the both terms, rebar yield strength and concrete bond strength, the development length design equation in dynamic state would be expressed above in 1.2 and 1.3 from ACI 318-19 and Eurocode 2, respectively. At this moment, if the DIF_b is smaller than DIF_s, development length in dynamic state requires longer length of rebar than one in static state. In other word, when the concrete structure impacted by dynamic loadings and it was designed only considering static state, improper bond failure could occur such as rebar pull-out or concrete splitting. For this reason, literature review on development length design method considering dynamic effect was done in current design codes and guidelines followed.

1. ACI 318-19 : Building code requirement for structural concrete

2. fib-bulletin 10 : Bond of reinforcement in concrete

3. ACI 308R-03 : Bond and development of straight reinforcing bars in tension

4. ASCE 59-1 : Blast protection of buildings

5. ACI 370R-14 : Report for the design of concrete structures for blast effects

6. UFC 3-340-02 : Structures to resist the effects of accidental explosions

However, as a result of review, no design codes and guidelines are considering dynamic effect on development length design, meaning that the development length is being designed under static loading only. Therefore, safety of the current design method of development length should be evaluated first and the new design method for development length is necessary if needed. DIF_b and DIF_s are compared to check it in this study, so suggested investigation of the current DIF_b is done at first

Jacques (2019) performed beam-splice test in static and dynamic loading conditions with shock tube in figure 1.2. The main variable was the diameter of the reinforcing steel, concrete cover depth, concrete compressive strength, and presence of transverse reinforcement.

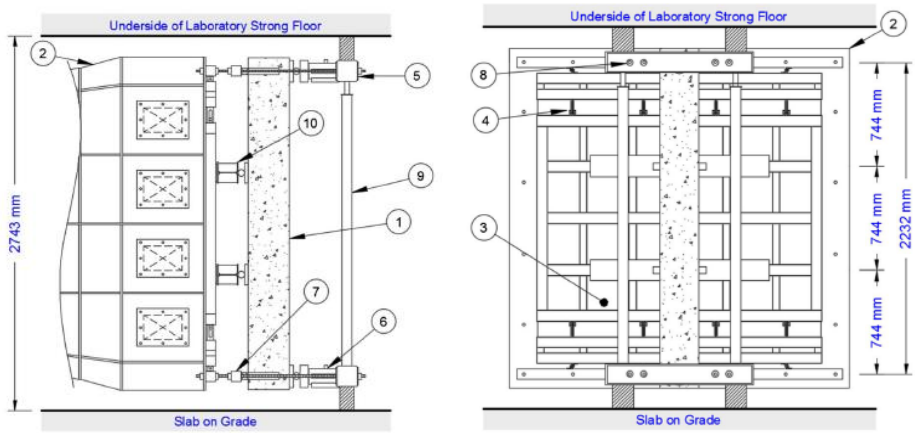


Figure 1.2 Beam-splice test setup with shock tube

As a result of the test, following development length equation is suggested, which is based on ACI 318 design code. However, this result is not presenting the bond DIF but the DIF for development length itself. Moreover, it would be said that the square root of concrete compressive strength with DIF is hard to be used for bond DIF.

$$l_{dd} = \frac{1}{DIF_{ld}} \left(\frac{3}{40} \frac{S_{f_y}}{\lambda \sqrt{S_{f'_c}}} \frac{\psi_t \psi_e \psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b \geq 300\,mm \qquad (1.4)$$

$$S_{f_y} = ASF \times DIF \ \ for\ steel$$

$$S_{f'_c} = ASF \times DIF \ \ for\ concrete$$

$$DIF_{ld} = -1.10 \times 10^{-5} l_d d_{cs} + 8.50 \times 10^{-4} A_b + 1.11 \geq 1.00$$

1.2. Research Objectives and Scope

There are two main objectives in this study. One of main objectives of this study is suggestion of new proper bon DIF equation. In this part, static and dynamic pull-out test with constant test technique was performed, and test data showing pull-out failure mode was used.

Another main objective is investigation of safety for the current development length design. With generated bond DIF in current study, it was compared with rebar yield DIF.

To be specific, for the first main objective, the pull-out test, it was divided in two section, preliminary test and main test. As mentioned above, to get test data only showing pull-out failure mode, rebar type and bond length are used as test variables in preliminary test. Once the specimen dimension selected, main pull-out test was performed in various loading speeds to get bond DIF in wide range of strain rate. Then, as described previous section, the development length in considering dynamic effect, the length could be changed with ratio of DIF_b and DIF_s. In same strain rate range, the DIF_b is compared to DIF_s for investigation of safety of current development length design.

1.3. Outline

Chapter 1 indicates the introduction such as the research background, objectives, scope, and outline of this study.

Chapter 2 presents concept of pull-out test and literature reviews of previous studies, and limitations of them.

Chapter 3 includes performance of pull-out test in static and dynamic state. Test method, designation, data acquisition, and post-processing are described in this chapter. As a result, bond DIF is suggested by the ratio bond strength in dynamic state to one in static state by regression analysis.

Chapter 4, once the bond DIF is obtained, it is compared with rebar yield strength DIF along the rebar strain rate to investigate safety of current development length design.

Finally, conclusions of this study are summarized in chapter 5.

2. Theoretical Background

Pull-out test is one of experimental methods to figure out the bond behavior between concrete and reinforcing steel including beam-splice test. Available concrete specimen would be cubed or cylindered and various types of reinforcing steel could be used. For the better understanding, the principle of pull-out test, first of all, will be briefly described, and possible failure modes will be expressed in this chapter. Then, characteristics and limitations of previous studies of pull-out tests were described.

2.1. Pull-out Test

2.1.1. Principle of pull-out test

Pull-out test would be said that it is one of tensile tests of reinforcing steel but the different thing is part of the rebar is placed in the concrete. Basically, the bond between reinforcing steel and concrete is governed by physical bonding with ribs of steel rather than chemical one, and when the ribbed reinforcing steel that was embedded in the concrete is getting tensile force, so-called pull-out, the physical mechanism are as follows.

1. As the slip occur between reinforcing steel and concrete, the concrete cover gets the radially-directional forces.

2. The forces make the concrete splitting if these are bigger than the confining forces, so-called hoop tension, from the concrete itself.

3. If there is external force to prevent the concrete splitting such as transverse reinforcement, spiral steel ring or the thick concrete cover, the pull-out failure might occur.

Currently, there is no specific standard of specimen in pull-out test design method, so the specimen design in this study was determined based on the specimens in previous studies. When mostly there were no mentions about specimen design methods, some of them indicated specimen design was followed according to RILEM RC6 recommendation.

In RILEM RC6 recommendation, the concrete specimen is cubed shape and has 10 times of the reinforcing steel diameter but bigger than 200mm. Then, the specimen is divided in two sections along its height, which are bond and de-bond zones. Here bond zone means the section where the reinforcing steel is embedded in the concrete when de-bond zone does not. Each zone has 5 times of the reinforcing steel diameter.

According to previous research of pull-out test review, the bond strength, in general, was getting bigger under dynamic loads scenario. Bond DIF was inversely proportional to the concrete compressive strength and bond length of the specimen. Especially, it was found that the bond DIF was affected critically by the failure mode of the specimen in pull-out test.

2.1.2. Failure mode in pull-out test

In pull-out test, based on the failure shape of specimen after the test it has 3 failure mode; pull-out, splitting, and rebar yields. Rebar yields failure mode is the case when the rebar yields before the concrete splits or the rebar is pulled out, and this is most ideal case in real concrete structure.

As mentioned in 2.1.1, as ribbed reinforcing steel displaced in pulled direction, the concrete cover dilates, and its dilation makes the cover splitting. And, when the confining force is bigger enough or other forces such as stirrups help it externally, the concrete is crushed along the transverse rib of the reinforcing steel, and, as a result, the pull-out failure occurs. In real concrete structure, those are ones of the improper bond failure and it must be prevented by enough development length of the rebar.

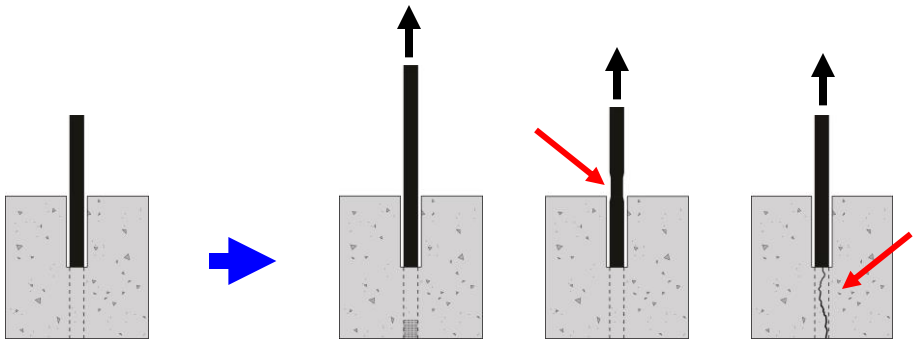
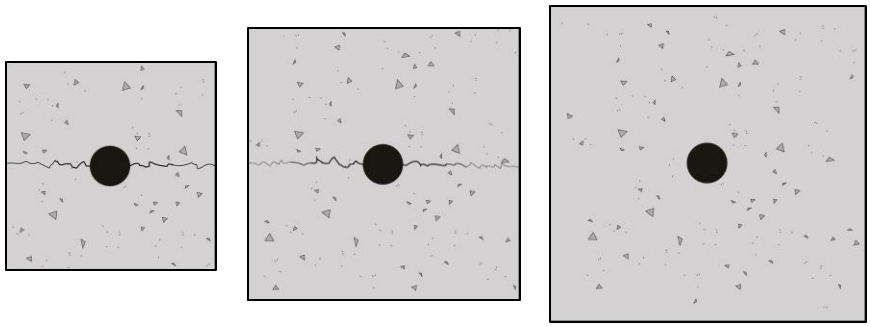


Figure 2.1 Failure modes in pull-out test

As ribbed reinforcing steel displaced in pulled direction, the concrete cover dilates, and its dilation makes the cover splitting. And, when the confining force is bigger enough or other forces such as stirrups help it

externally, the concrete is crushed along the transverse rib of the reinforcing steel, and, as a result, the pull-out failure occurs. In real concrete structure, those are ones of the improper bond failure and it must be prevented by enough development length of the rebar.

Especially, in splitting failure mode, the maximum potential bond stress is not generated. If there are no external factors helping confining forces of the concrete cover against the concrete's dilation by displacement of the ribbed reinforcing steel, and the concrete cover has to deal with it by itself, the failure mode between splitting and pull-out failure mode would depend on the dimension of concrete specimen.



<Case 1> <Case 2> <Case 3>

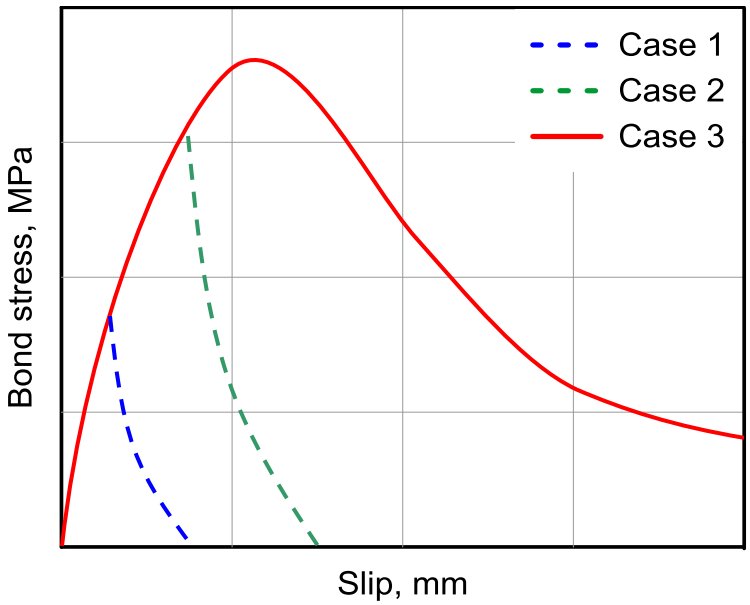


Figure 2.2 Concept curve of bond stress vs. slip on specimen dimension cases

To be specific, the concrete dimension is not big enough compared to the reinforcing steel in case 1 and 2 in figure 1.3. And if bond length and dimension of reinforcing steel are constant in case 1 through 3, the bond stress versus slip curve should be same with the curve, red line in figure 1.4, of case 3 in case no splitting occur on concrete of specimen.

However, once the concrete splits like case 1 and 2, the bond stress drops before it reaches the maximum potential bond stress. And it was assumed that dropping moment is barely predictable correctly under dynamic pull-out test compared to static one. Moreover, the bond DIF in pull-out test with splitting failure mode was relatively bigger than one with pull-out failure mode.

Therefore, failure mode in pull-out test was one of focusing points in this study, and it was concluded that the test data with specimens showing pull-out failure mode only should be used to get the proper bond DIF in pull-out test. So, the literature review was done on failure mode in pull-out test intensively in next section.

2.2. Previous Studies

2.2.1. Pull-out test in high loading rate

2.2.1.1 Weathersby, J. H (2003)

Weathersby performed pull-out test in 3 loading cases, static, dynamic and impact. The main variables were the reinforcing steel diameter and specimen diameter, which connected to c/d_b ratio.

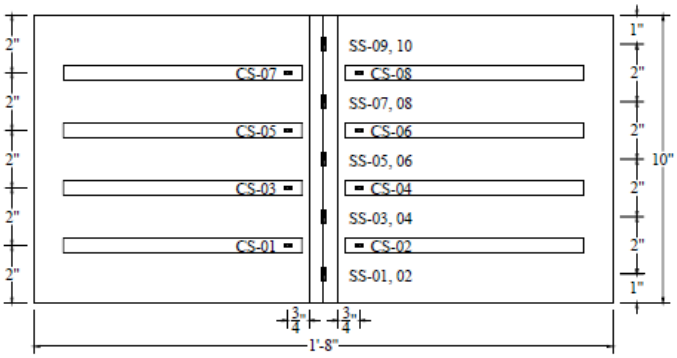


Figure 2.3 Pull-out test specimen (Weathersby, J. H. 2003)

By test result it was found that the specimen with bigger c/d_b shows the better resistance ability of bonding. And as the perspective of the failure mode, for all specimen with ribbed reinforcing steel show splitting or rebar yields failure mode. There was one case even show different failure mode between static and dynamic pull-out test.

2.2.1.2 George, S and M. Berra (2010)

In this research, the concrete compressive strength and bond length were main test variables. The pull-out test was done with Split-Hopkinson-pressure bar and the failure mode was controlled by author. To be specific, the steel tube was placed around the concrete specimen as shown in figure 2.4 and it was providing external confining force to prevent the concrete splitting.

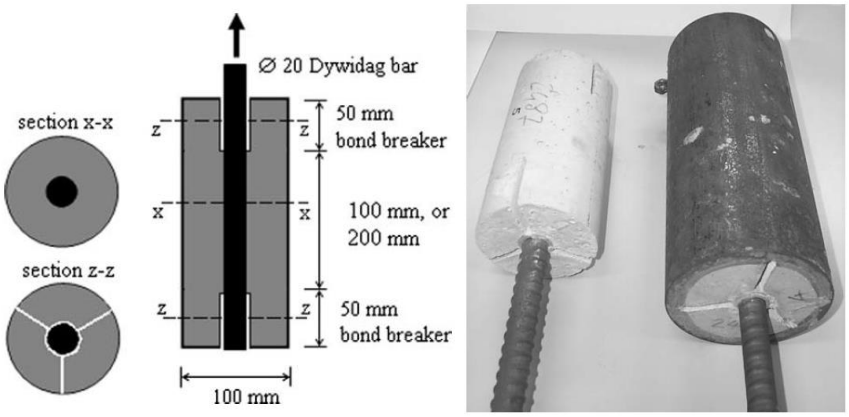


Figure 2.4 Pull-out test specimen (Geroge, Sand M. Berra. 2010)

As a result, it was indicated that the concrete compressive strength and bond length are inversely proportional to bond DIF. The concrete specimen splits without steel tube, and two cases of specimens with steel tube had shown pull-out failure mode.

2.2.1.3 Maca, P et al (2016)

The only variable in this study was loading rate, and one case of the test was performed. One of the most important thing in this research was that for the static state the pull-out test was perform when push-in test was done for the dynamic state. Although the specimen in static and dynamic state shows the pull-out failure mode, according to research from Yan in 1998, the test results of bond strength between pull-out and push-in test were not constant.

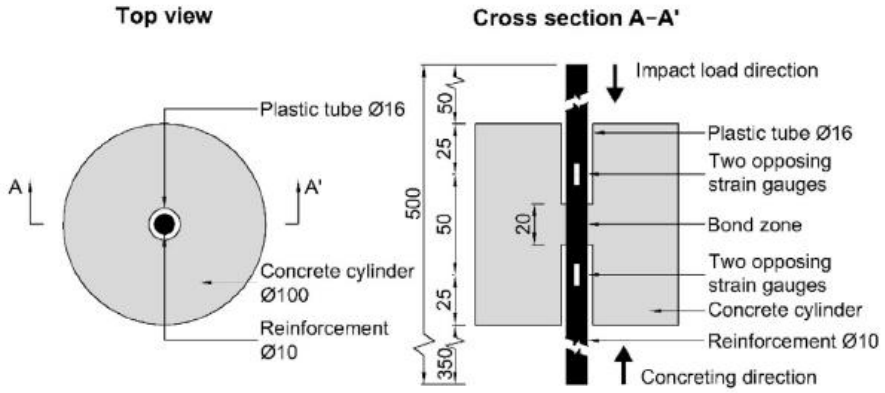


Figure 2.5 Pull-out test specimen (Maca, P et al. 2016)

2.2.2. Summary and limitations of previous studies

To summarize, as the previous studies were reviewed perspective to failure mode in pull-out test, it was shown that the test cases showing pull-out failure mode is too short in table 2.1. To be specific, on 2.2.1.1 there was no test data with specimen of ribbed reinforcing steel showing pull-out failure mode. The external confinement, the steel tube around the concrete specimen in 2.2.1.2 forces the specimen to show pull-out failure mode. And in 2.2.1.3, different experimental techniques for static and dynamic test were used.

Table 2.1 Pull-out failure mode in previous studies

Author	Variables	Failure mode*	Pull-out failure cases
Weathersby	d_b, B	S, Y	0
Solomos	d_b, f'_c	S, P	2
Maca	-	P	1

* S: splitting, P: Pull-out, Y: Rebar yields

Therefore, with currently existing cases of dynamic pull-out test are judged that they are hard to be used to suggest bond DIF properly. So in the current study, first of all, pull-out test was performed with constant test technique in static and dynamic state. Then in preliminary test the specimen design that will be used in main pull-out test was selected to make sure the all specimens show pull-out failure mode. In main pull-out test, the loading speed was the variable to get bond DIF along the reinforcing steel strain rate.

3. Experimental Program

In this chapter, the whole procedure of the tests performed in this study is described including material and pull-out test. Material tests composed with concrete compressive test and reinforcing steel tensile test in static state. Test data from the material test was used to calculate needed data in pull-out test. For pull-out test, as described in previous chapter, it was performed with two phases, preliminary and main pull-out tests. Test objectives, designation, method, data acquisition, and data post-processing were presented on detail. Then, with the test result data the bond DIF is suggested in this chapter.

3.1. Material test

3.1.1. Concrete compressive test

Concrete compressive test was performed with MTS 815 equipment in Seoul National University building number 35 based on ASTM C39/C38M-16b. The target concrete compressive strength was 30MPa, and mixture ratio is described in table 3.1. Test was done with loading rate of 0.5mm/min (displacement control), and the data was obtained with load cell in the machine and LVDT of extensometer. For the concrete used in preliminary test, total two batches were used because of the its scale. For each batch, three specimens were made and tested, and the average compressive strength was 27 and 25MPa. With same test method compressive test and mixture ratio for concrete used in

main pull-out test was performed with total six specimens, and the average test result was 25MPa.

Figure 3.1 Concrete compressive test setup

Table 3.1 Concrete mix proportion

f_c', MPa	G_{max}, mm	W/B, %	S/a, %	Unit weight, kg/m^3			
				W	C	S	G
30	25	48	47	165	344	860	968

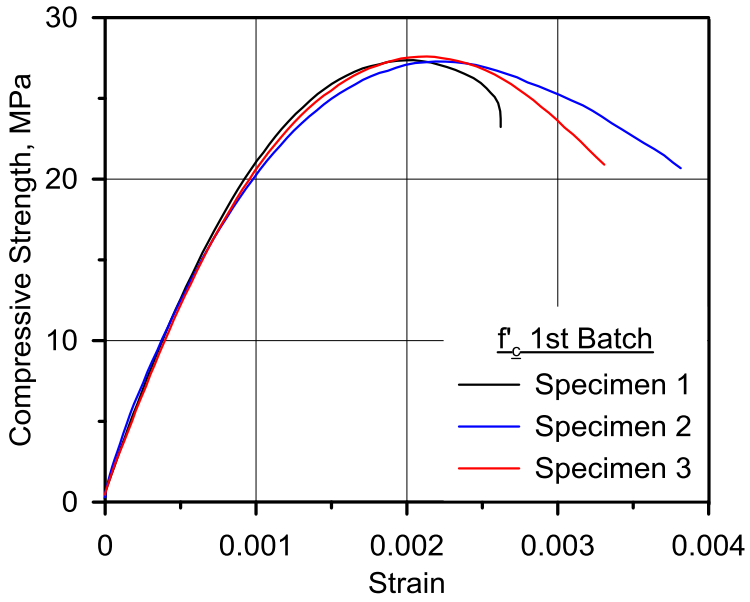


Figure 3.2 stress vs. strain curve of 1st batch concrete compressive test

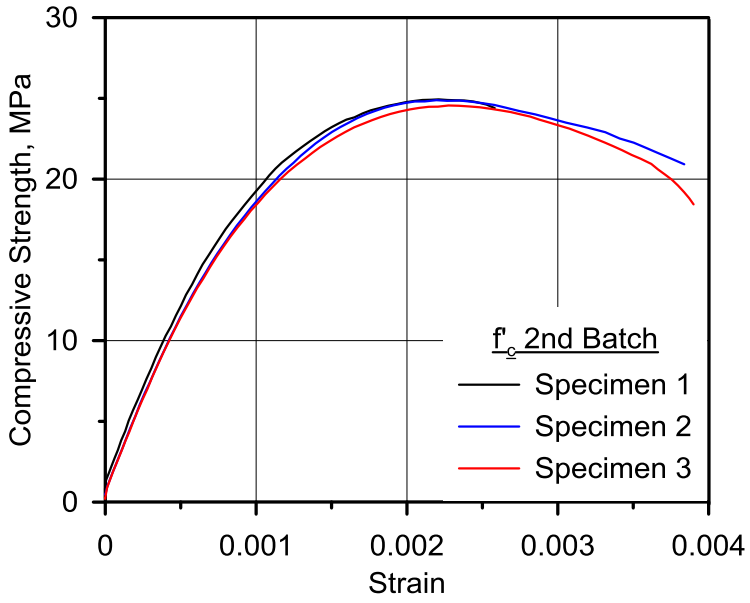


Figure 3.3 Stress vs. strain curve of 2nd batch concrete compressive test

3.1.2. Reinforcing steel tensile test

Reinforcing steel tensile test was performed with MTS 810 equipment in Seoul National University building number 35 based on ASTM A615 and A370. The rebar diameter was D19, and S400 and S600 yield strength were used with 1mm/min displacement control loading rate. Three specimens were tested for each types of reinforcing steel. The load cell in the machine was used for strength and the strain gauge which was used in pull-out test as well was used for verification. The test result is shown in table 3.2.

Figure 3.4 Rebar tensile test setup

Strain gauges were mounted longitudinal ribs on the reinforcing steel in different positions considering the exist of transverse ribs. This is because the bond strength from pull-out test will be calculated with the nominal diameter,

19.1mm, of the reinforcing steel but it was expected that the elasticity of modulus will be affected the exist of transverse ribs because the actual diameter of reinforcing steel will be different. So, in this study, as shown in figure 3.3, two strain gauges were mounted for reinforcing steel tensile test for the better calculation of bond strength from pull-out test.

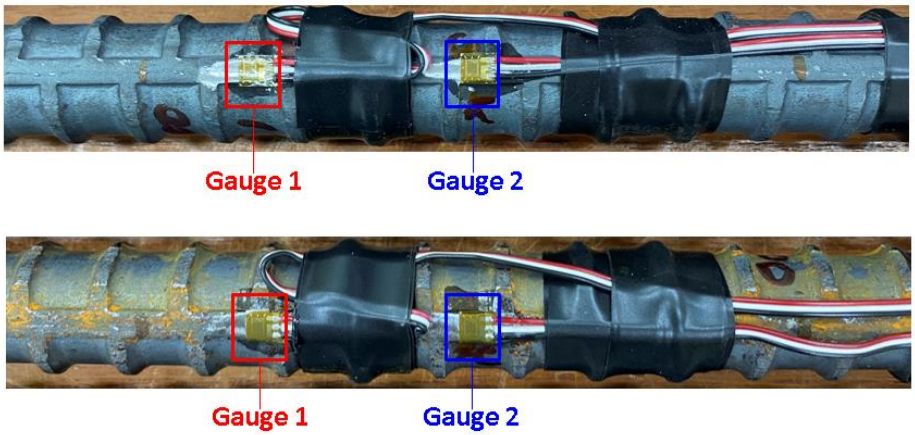


Figure 3.5 Position of strain gauges for rebar tensile test

Table 3.2 Rebar tensile test result

Grade	Strain gauge	Yield strength, MPa	Elasticity of modulus, MPa
S400	1	451.4	189,622
	2		188,440
S600	1	616.1	199,254
	2		182,216

The test result is described in table 3.2. Figures 3.3 and 3.4 are one of test result curve with strain versus stress, and rest of them would be found in appendix section. As presented here, test data of S400 reinforcing steel show

almost constant values of elasticity of modulus regardless of exist of transverse rib. However, slightly different values of elasticity of modulus were found in S600 reinforcing steel. So, for the strain gauge mount in pull-out test specimens the exist of transvers rib was regarded. Strain gauge was C4A-06-060SL-350-39P.

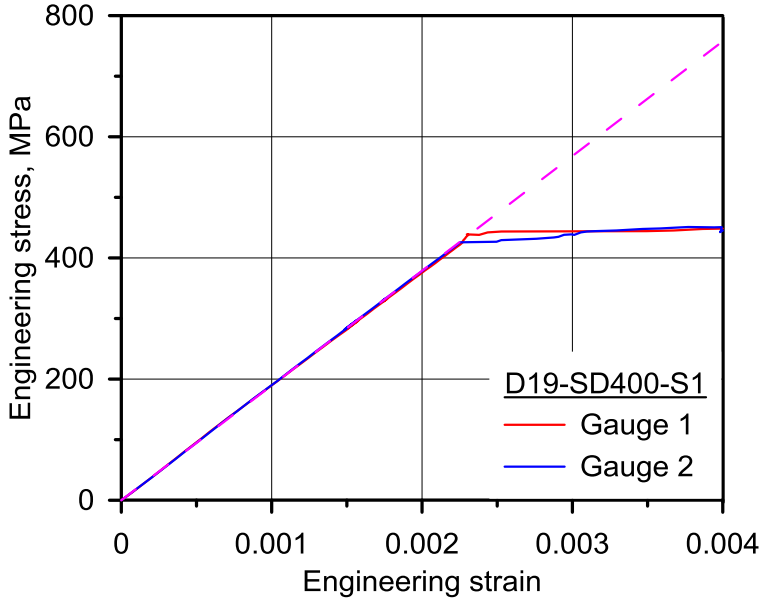


Figure 3.6 Stress vs. strain curve of S400 rebar tensile test

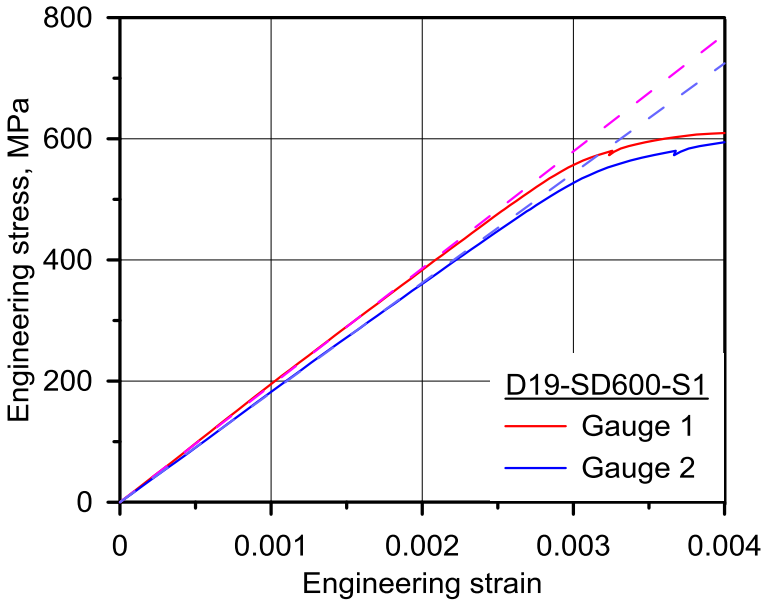


Figure 3.7 Stress vs. strain curve of S600 rebar tensile test

3.2. Preliminary pull-out test

The main objective of preliminary pull-out test was to determine specimen design will be used in main pull-out test. The standard was the failure mode because in this study the bond DIF will be suggested with test specimen only showing pull-out failure mode in static and dynamic tests. In the table 3.3, test variable is presented.

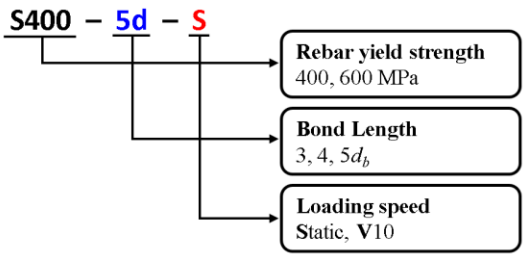


Figure 3.8 Test specimen designation

Table 3.3 Variables of preliminary pull-out test

Rebar yield strength	Bond length	Loading speed
400, 600 MPa	3, 4, 5d_b	Static, 10 m/s

3.2.1. Specimen preparation

Currently, there is no specific design criteria for pull-out test specimens, and it was found that lots of previous studies were using RILEM RC6 recommendation for specimen design. According to this recommendation, the specimen design was being done considering the reinforcing steel dimension. To be specific, the specimen width shall be ten times of used reinforcing steel diameter and bigger than two hundred millimeters, and it has five times of reinforcing steel diameter for both bond and de-bond zone. In the bond zone, the concrete will be placed with reinforcing steel. PVC pipe will be mounted before concrete placement to detach concrete from reinforcing steel in the de-bond zone.

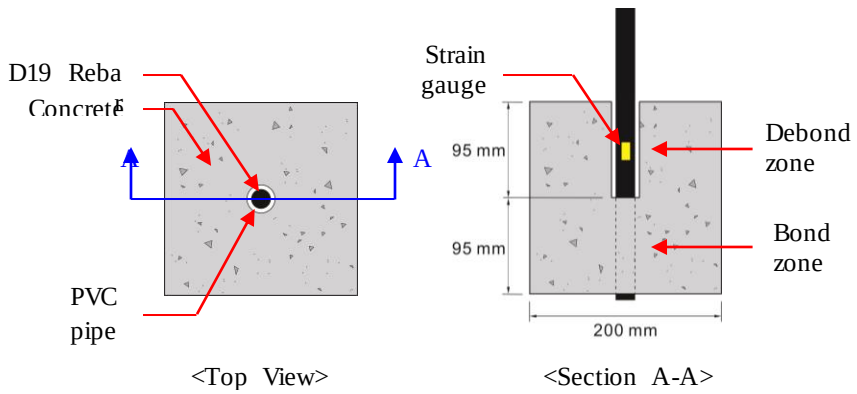


Figure 3.9 Designed specimen dimension

Based on RILEM RC6, specimens were design as shown in figure 3.9. The total height was made with sum of five times of the reinforcing steel diameter and bond length. Bond length was one of variables in preliminary pull-out test, which were three, four, and five times of the reinforcing steel diameter. This is

because there were some cases showed splitting failure mode with bond length five times of the reinforcing steel diameter in pull-out test in previous studies. So, to make sure that the pull-out failure mode is presented in this study, the bond length is selected as one of variables in preliminary pull-out test. Strain gauges were mounted longitudinal rib on reinforcing steel in de-bond zone inside the PVC pipe.

In specimen preparation, following two things were considered critically before the concrete placement;

1. Constant amount of transverse ribs in bond length

2. Verticality of reinforcing steel

First one is constant amount of transverse ribs in bond length. This is because in pull-out test, the bond behavior between concrete and reinforcing steel is more governed by physical bonding than chemical one. Therefore, before the concrete placement, nine, twelve, and fifteen transverse ribs were constantly maintained for bond length three, four, and five times of the reinforcing steel diameter.

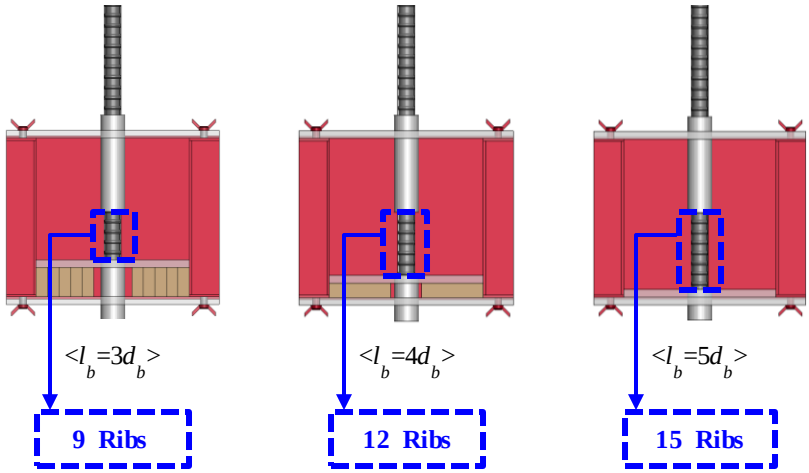


Figure 3.10 Amount of transverse ribs along the bond zone

Second procedure is about verticality of reinforcing steel in specimen. If the verticality is not maintained well, the result of pull-out test would be different totally. To deal with it, the PVC pipe which is same one for de-bond zone is placed in the free end part of reinforcing steel in green dashed line in figure 3.12, and make sure that the reinforcing steel has constant heights along spots A, B and C. At this moment, the diameter of the reinforcing steel is smaller than the inner diameter of PVC pipe, so it was making the gap between them. So, it was compensated by taping the reinforcing steel on spot A, B and C with constant thickness.

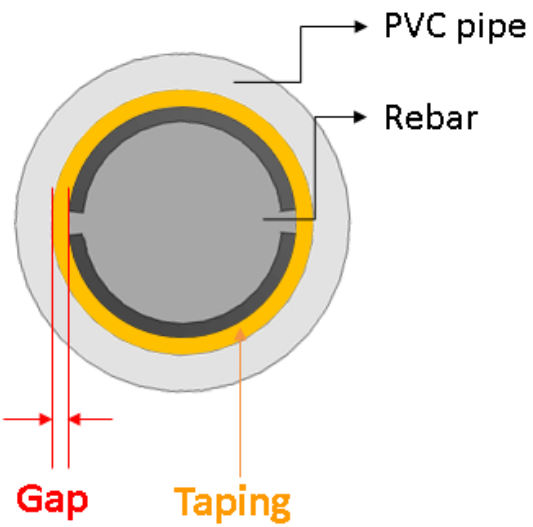


Figure 3.11 Compensation of gap between PVC pipe and rebar

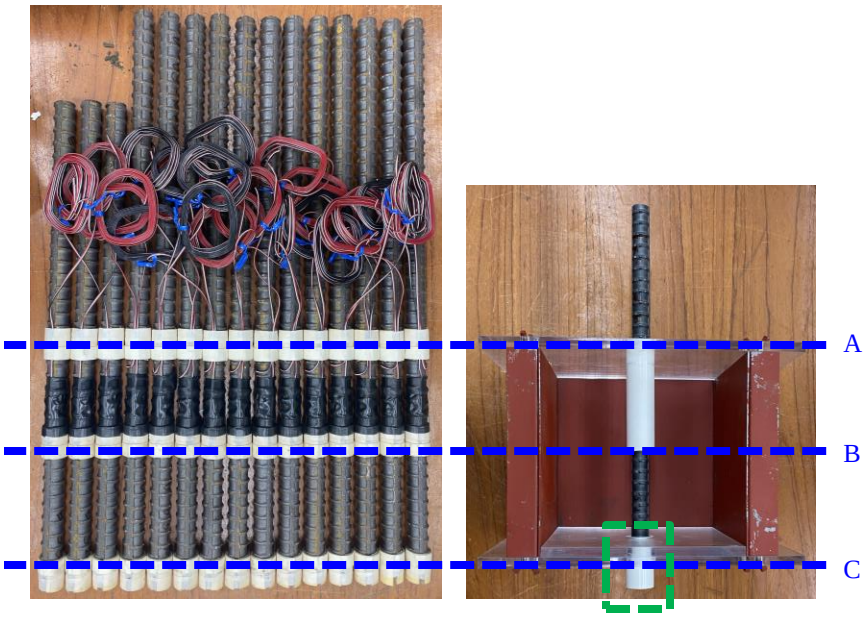


Figure 3.12 Rebar verticality maintain method

Once the concrete is placed, for specimens in preliminary pull-out test the verticality was verified with leveler as shown in figure 3.13 by measuring and comparing angles between sections of concrete and reinforcing steel. As described in table 3.4, the average tolerance was 0.095° and it could be said the verticality is maintained well.

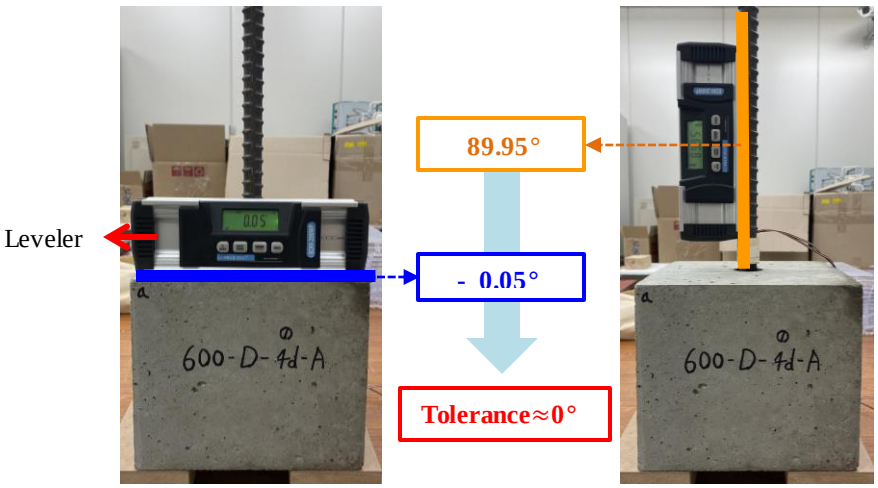


Figure 3.13 Rebar verticality verification method

Table 3.4 Verification result of rebar verticality

Specimen Name	Concrete side 1 (°)			Concrete side 2 (°)		
	Concrete	Rebar	Tolerance	Concrete	Rebar	Tolerance
600-5d-S	0.05	90.10	0.05	0.05	90.20	0.15
600-5d-D-1	0.05	90.05	0.00	0.25	90.05	0.20
600-5d-D-2	0.00	90.15	0.15	0.15	90.20	0.05
600-4d-S	0.20	90.30	0.10	0.20	90.30	0.10
600-4d-D-1	0.05	90.05	0.00	0.35	90.40	0.05
600-4d-D-2	0.10	90.15	0.05	0.25	90.10	0.15
600-3d-S	0.15	90.05	0.00	0.20	90.25	0.05
600-3d-D-1	0.15	90.10	0.05	0.25	90.35	0.10
600-3d-D-2	0.15	90.35	0.20	0.25	90.10	0.15
400-5d-S	0.05	90.45	0.40	0.00	90.05	0.05
400-5d-D-1	0.05	90.05	0.00	0.25	90.20	0.05
400-5d-D-1	0.05	90.25	0.20	0.05	90.05	0.00

3.2.2. Preliminary pull-test procedure

MTS 810 in Seoul National University building number 35 in Figure 3.14 was used for static preliminary pull-out test, and the loading rate was 0.5mm/min. The bond strength was calculated with data from reinforcing steel strain gauge and compared with ones from load cell.

The strain gauge was the same one used in reinforcing steel tensile test. It was mounted on longitudinal rib of steel. The slip, as shown in figure 3.16, was obtained from the relative displacement between concrete and reinforcing steel sections by LVDT.

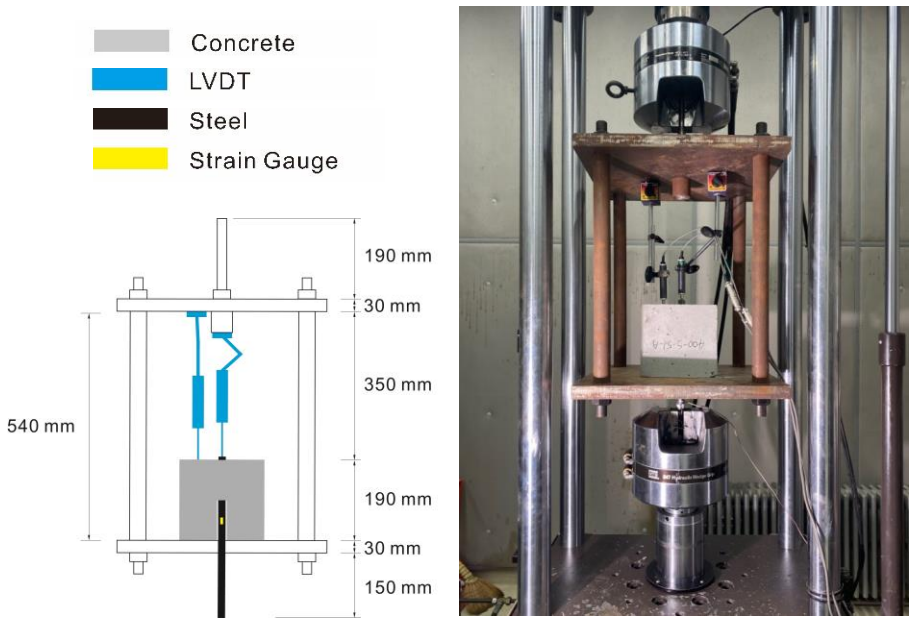


Figure 3.14 Static pull-out test setup

High speed hydraulic machine of Extreme performance testing center in Seoul National University building was used for dynamic preliminary pull-out test. The machine has capacity in tension force 330kN in 10m/s velocity. The loading rate was 10m/s in preliminary pull-out test. This is because it was assumed that if the specimen in 10m/s loading rate show pull-out failure mode, others will make same failure mode in lower loading rates.

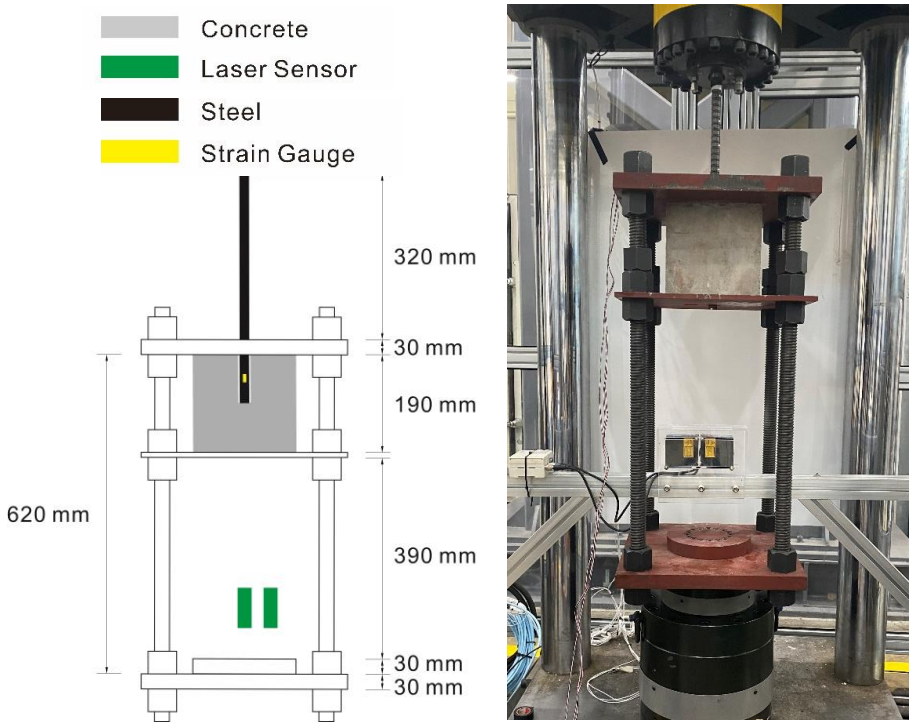


Figure 3.15 Dynamic pull-out test setup

Data acquisition for bond strength was same as one from static pull-out test, which was calculated from reinforcing steel strain gauge. The slip was measured by comparison of displacement between concrete and reinforcing steel free end sections by two lasers rather than LVDT for the better sensitivities.

Laser sensors, as shown in figure 3.15, mounted in aluminum profile frame away from the test steel frame plate to avoid any vibration from machine itself.

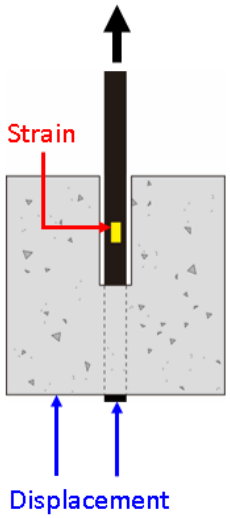


Figure 3.16 Data acquisition points in specimen

Moreover, in dynamic pull-out test, Dewetron DAQ system was used with 1Mhz data sampling rate. Used filtering type was Butter worth and low-pass cutoff frequency was 300kHz to avoid any change between test result data before and after filtering. Lastly, to observe the shape of the reinforcing steel and the overlook of test two high speed cameras, Phantom V711 and Photron FASTCAM SA-Z with 50,000, 10,000 fps frame rate, respectively, were used.

Figure 3.17 High-speed camera 1 (photron FASTCAM SA-Z)

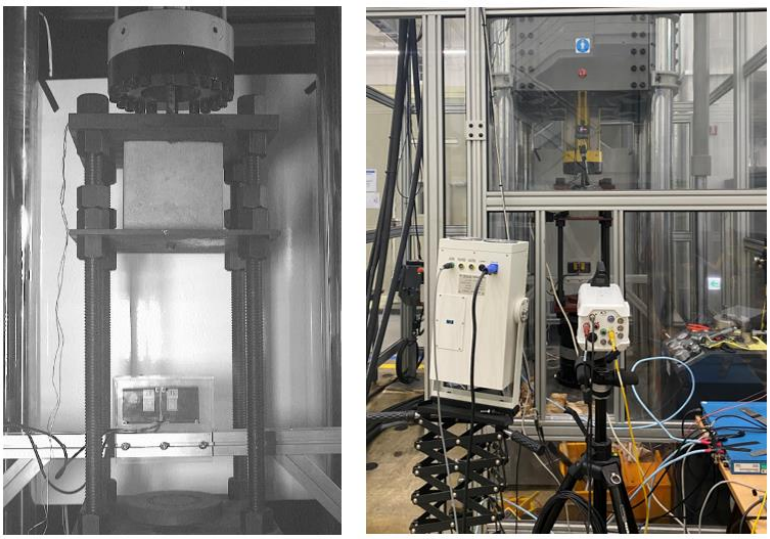


Figure 3.18 High-speed camera 2 (phantom V711)

As mentioned previously, the bond stress was calculated from the reinforcing steel strain gauge with material properties obtained from rebar tensile test. To be specific, elasticity of modulus of the reinforcing steel from rebar tensile test was multiplied with strain value and D19 rebar nominal area. And, it was divided by the bonded area between the reinforcing steel and concrete in bond zone.

$$F = E\varepsilon A_s \tag{3.1}$$

$$\tau = \frac{F}{l_b \pi d_b} = \frac{E\varepsilon A_s}{l_b \pi d_b} \quad (l_b = 3, 4, 5 d_b) \tag{3.2}$$

Bond DIF was calculated with ratio of bond stress in dynamic pull-out test to one in state pull-out test.

$$DIF_b = \frac{\tau_{dynamic}}{\tau_{static}} = \frac{(Dynamic\ bond\ stress)}{(Static\ bond\ stress)} \tag{3.3}$$

For strain rate, once the strain values are obtained from the reinforcing steel strain gauge and the strain versus time curve is made, it was calculated with the slope between two points where the strain value is zero and maximum.

$$\dot{\varepsilon} = \frac{\varepsilon_2 - \varepsilon_1}{t_2 - t_1} \tag{3.4}$$

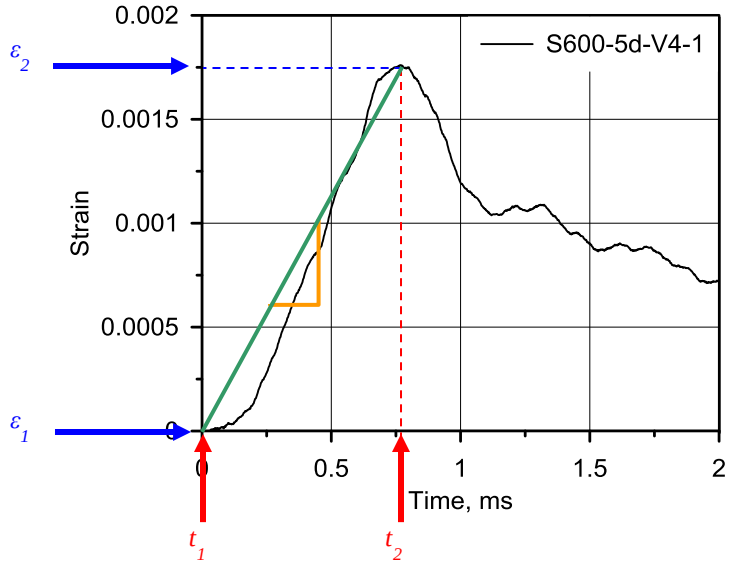


Figure 3.19 Strain rate calculation method

3.2.3 Preliminary pull-out test results

As mentioned in previous section, the main purpose of the preliminary pull-out test was to decide the specimen design in the main pull-out test. To be specific, specimen should be determined which is only showing the pull-out failure mode. As the failure mode in pull-out test is three kinds, pull-out, splitting, and rebar yield, first of all, the reinforcing steel is checked whether it is yielded or not.

From the reinforcing steel tensile test, the yield strain points for S400 and S600 are 0.0021 and 0.0031, respectively. First, the strain value versus time curve is drawn with the test data in static and dynamic pull-out test to compare with yield strain points as shown in figure 3.20 and 3.21. It was found that the strain value from all specimen in static pull-out test did not exceed the yield strain point.

In the dynamic pull-out test, the S400 reinforcing steel has yielded based on the comparison with yield strain point from tensile test. As a result, S600 reinforcing steel has been used in the main pull-out test. However, the reinforcing steel yield strain point was determined in tensile rebar test, and the material property of the reinforcing steel would be changed in dynamic state.

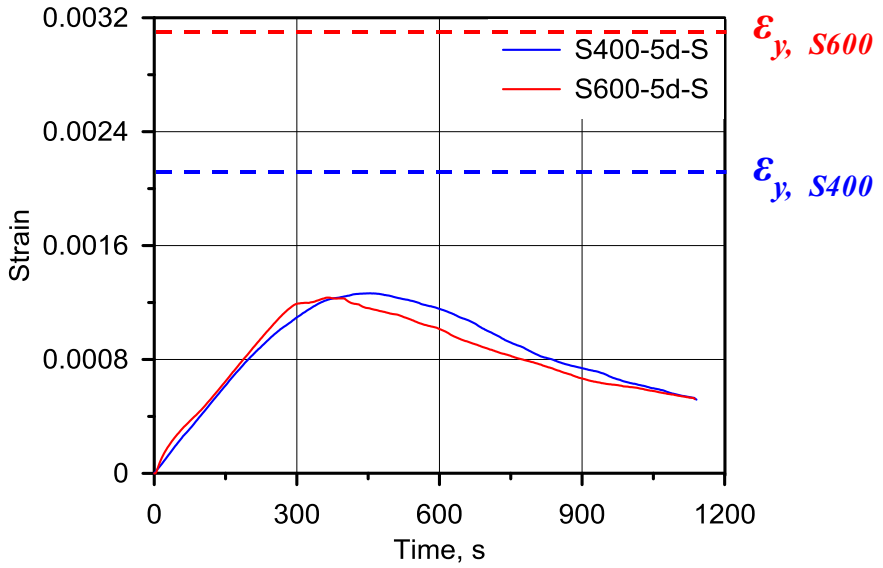


Figure 3.20 Strain vs. time curve in preliminary static pull-out test

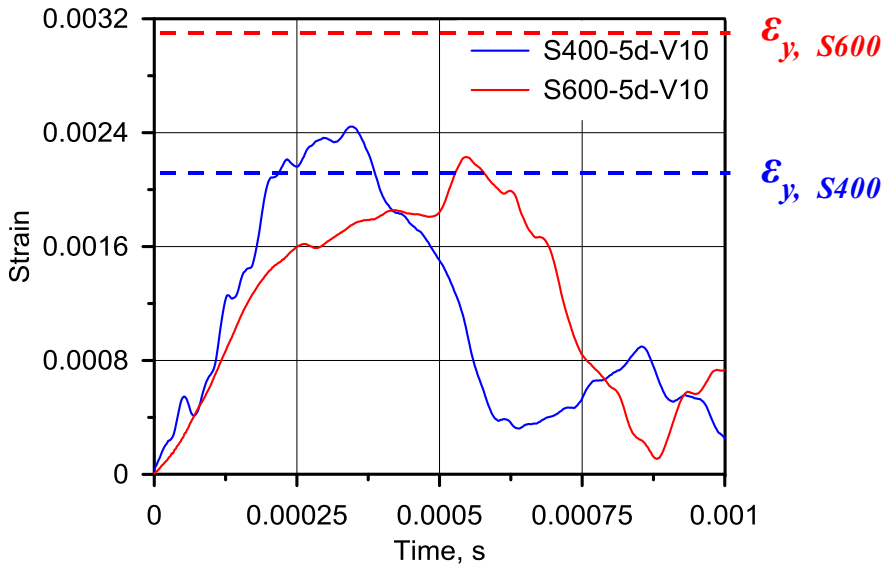


Figure 3.21 Strain vs. time curve in preliminary dynamic pull-out test

Next, the failure shape on concrete of the specimen is observed. As presented in table 3.5, pull-out failure mode was observed in static and dynamic pull-out test for all specimens. In dynamic pull-out test, if we only focus on the perspective of the concrete failure shape, the specimen with S400 reinforcing steel also show the pull-out failure mode. However, since the S400 reinforcing steel has yielded, as a result, the specimen for main pull-out test is determined with S600 rebar and $5d_b$ bond length.

Table 3.5 Failure mode in preliminary pull-out test

Rebar	Bond length	Static test	Dynamic test
S400	$5d_b$	Pull-out	Rebar yields
S600	$5d_b$	Pull-out	Pull-out
	$4d_b$	Pull-out	Pull-out
	$3d_b$	Pull-out	Pull-out

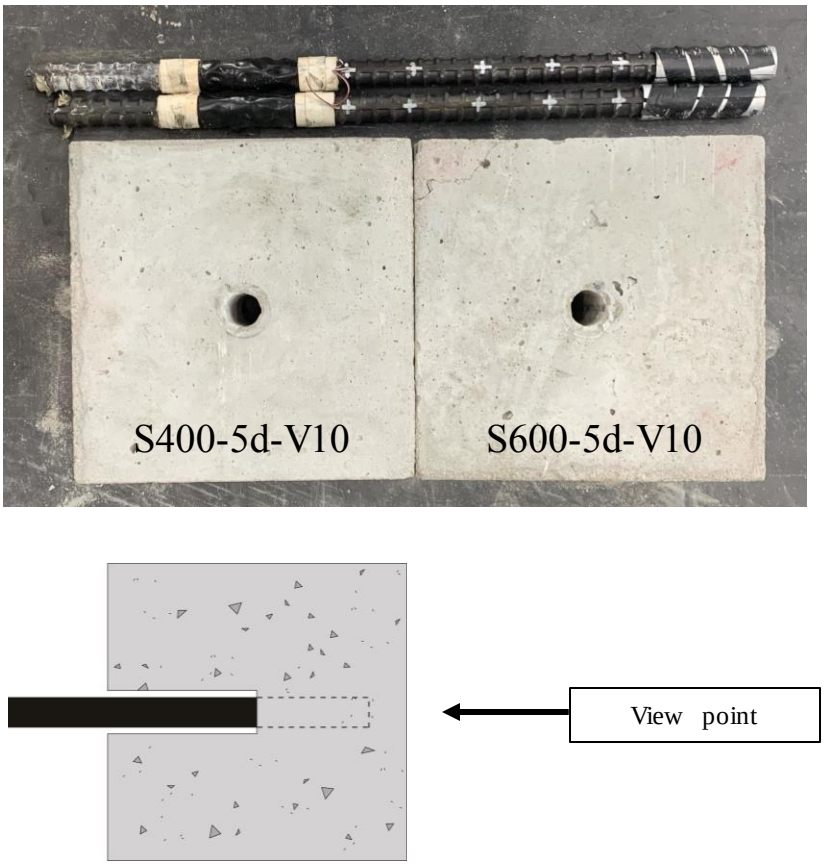


Figure 3.22 Failure mode after preliminary pull-out test

3.3. Main pull-out test

The main objective of main pull-out test was to suggest new bond DIF along the various rebar strain rate. Then, it was compared with steel yield strength DIF to evaluate the safety of the current development length design method. The only variable for the test was loading rates to get bond DIF along the various strain rate range, which was static, 1, 4, 7, and 10m/s.

The material test result of concrete and reinforcing steel for main pull-out test is shown table 3.6. The reinforcing steel was same as the preliminary test but the concrete was placed newly.

Table 3.6 Material test result for main pull-out test

Concrete	Rebar	
$f'c$ (MPa)	f_y (MPa)	E (MPa)
25	616	199,254

3.3.1 Main pull-out test procedure

Test procedure for the main pull-out test is same as one for the preliminary pull-out test including the specimen design method, designation, data acquisition and data post-processing. All specimens have S600 reinforcing steel and $5d_b$ bond length, and three specimens for each loading rate were tested.

3.3.2 Main pull-out test results

As mentioned in previous sections, the test data that is only showing pull-out failure mode in static and dynamic pull-out test was used for the suggested bond DIF. Figures from 3.23 to 3.27 are presenting the failure shape of concrete specimen after the test, and all specimens in static and dynamic pull-out test show the pull-out failure mode.

Figure 3.23 Failure mode after pull-out test (static)

Figure 3.24 Failure mode after pull-out test (1 m/s)

Figure 3.25 Failure mode after pull-out test (4 m/s)

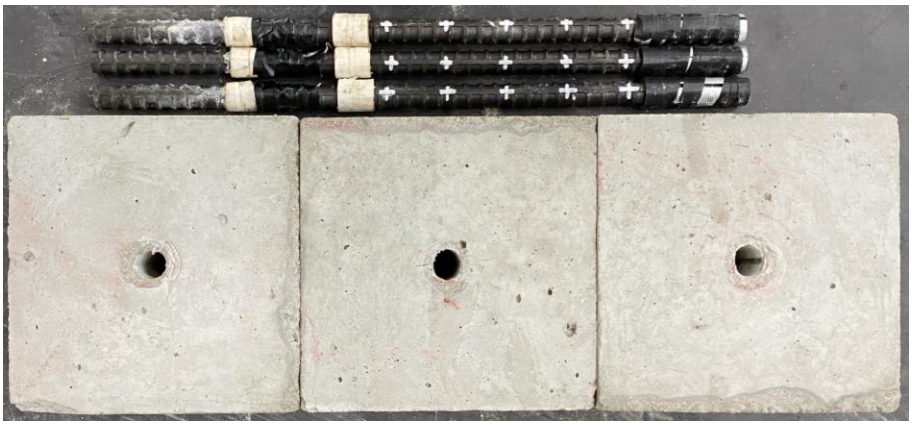


Figure 3.26 Failure mode after pull-out test (7 m/s)

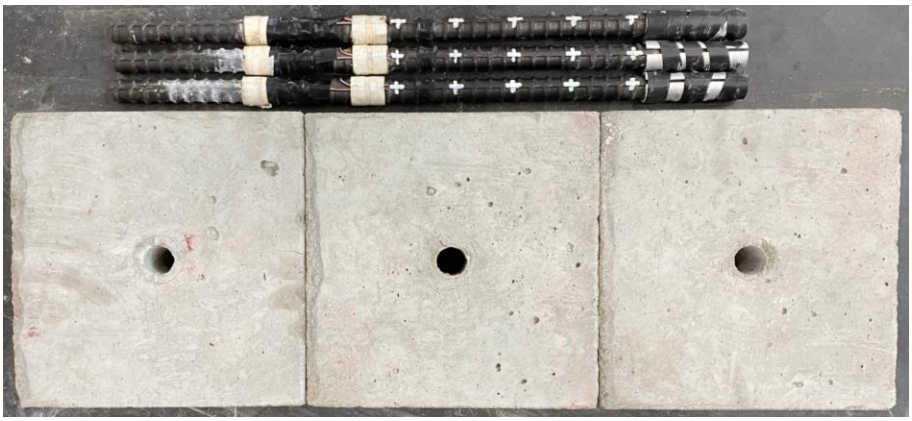


Figure 3.27 Failure mode after pull-out test (10 m/s)

Moreover, the reinforcing steel was also checked whether it was yielded or not by comparing the strain yield point from rebar tensile test and strain value from strain gauge in pull-out test. With curves from figure 3.28 to 3.32 of strain value versus time, it was found that no reinforcing steel used in specimens has yielded during the test.

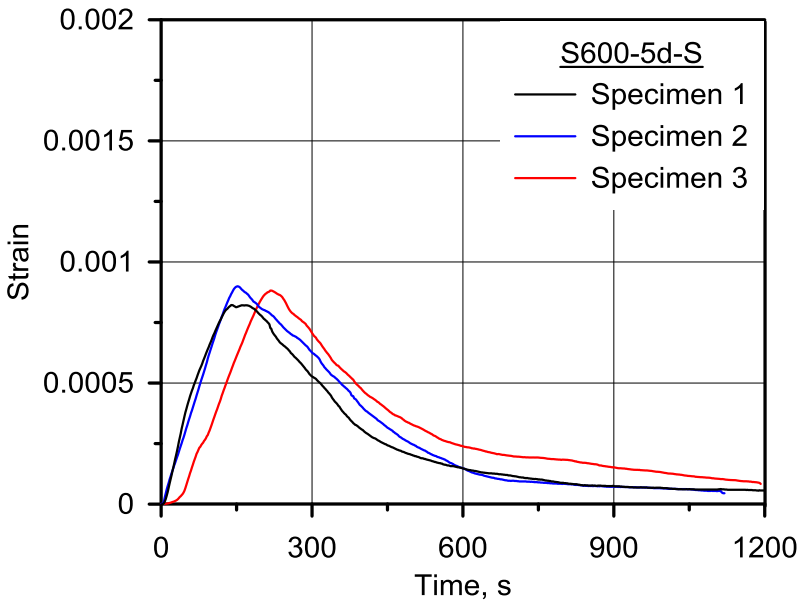


Figure 3.28 Strain vs. time curve (static)

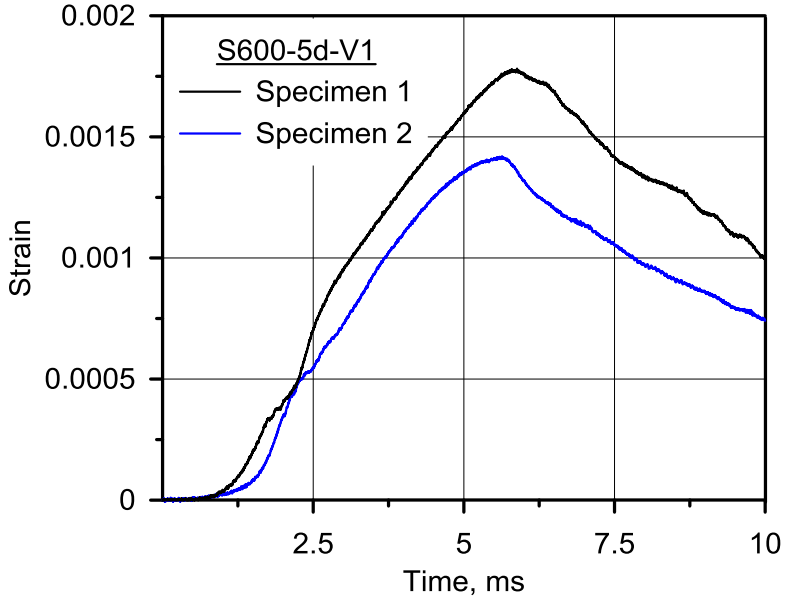


Figure 3.29 Strain vs. time curve (1 m/s)

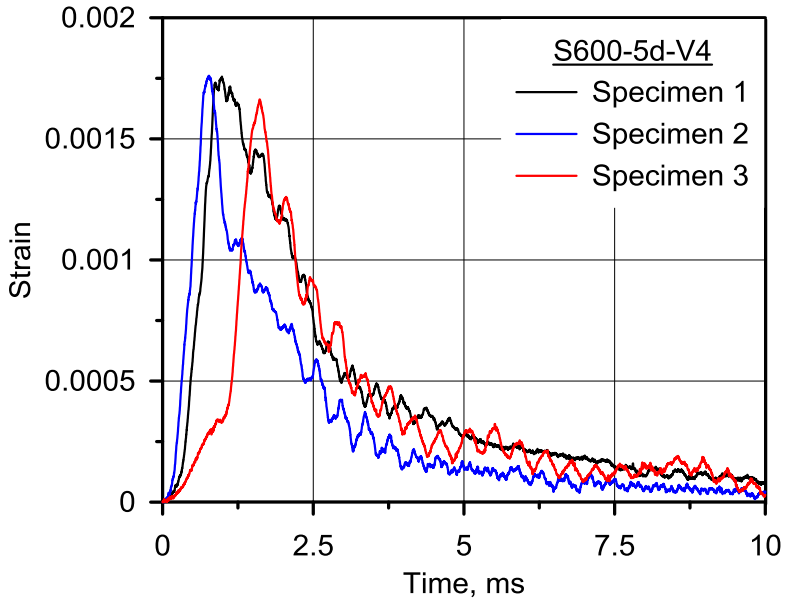


Figure 3.30 Strain vs. time curve (4 m/s)

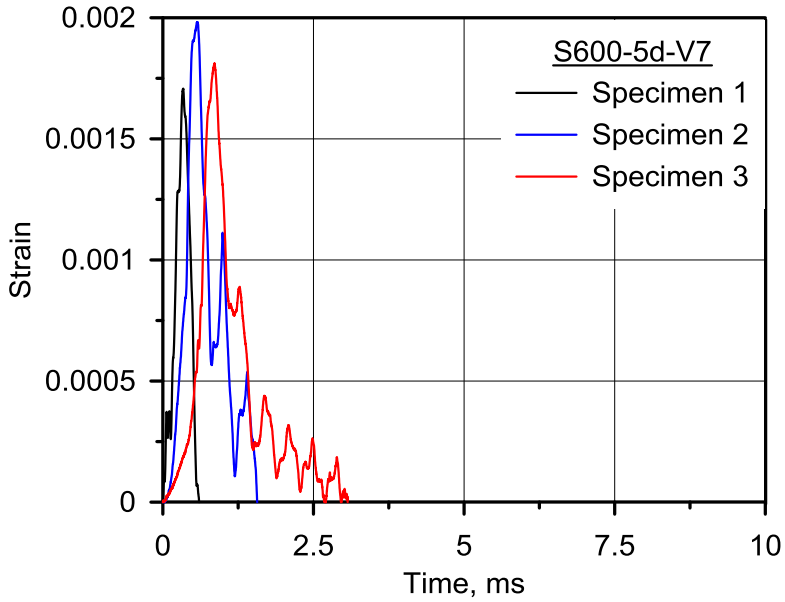


Figure 3.31 Strain vs. time curve (7 m/s)

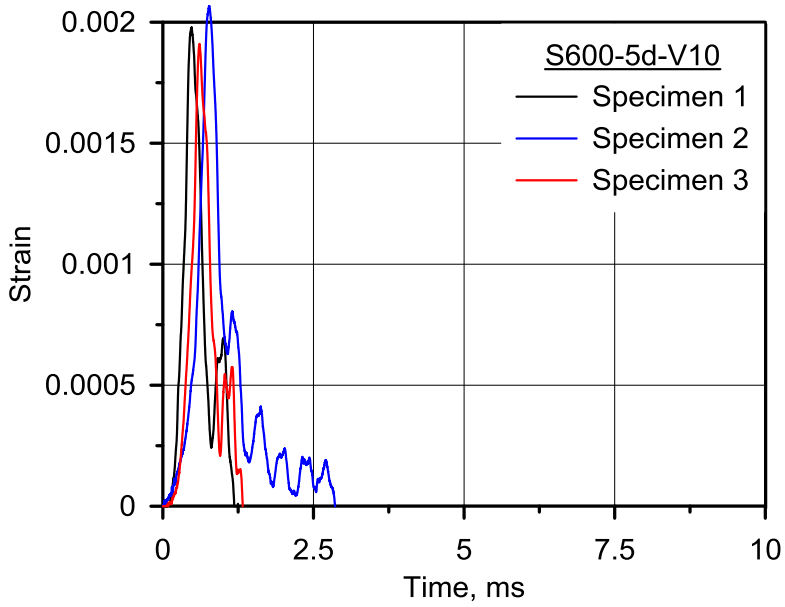


Figure 3.32 Strain vs. time curve (10 m/s)

Lastly, bond DIF is calculated with the ratio of bond strength between static and dynamic test with data that is showing pull-out failure mode. Following curves are bond stress versus slip between concrete and the reinforcing steel. And the test result on detail would be seen in table 3.7.

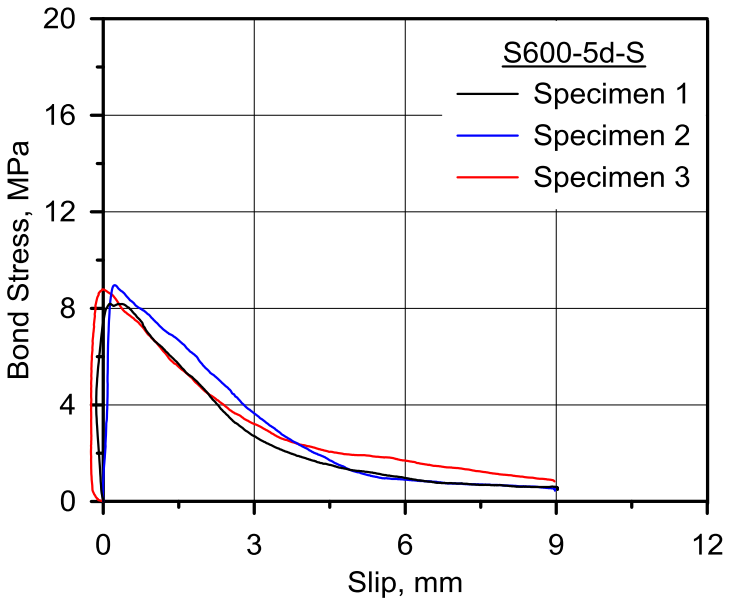


Figure 3.33 Bond stress vs. slip curve (static)

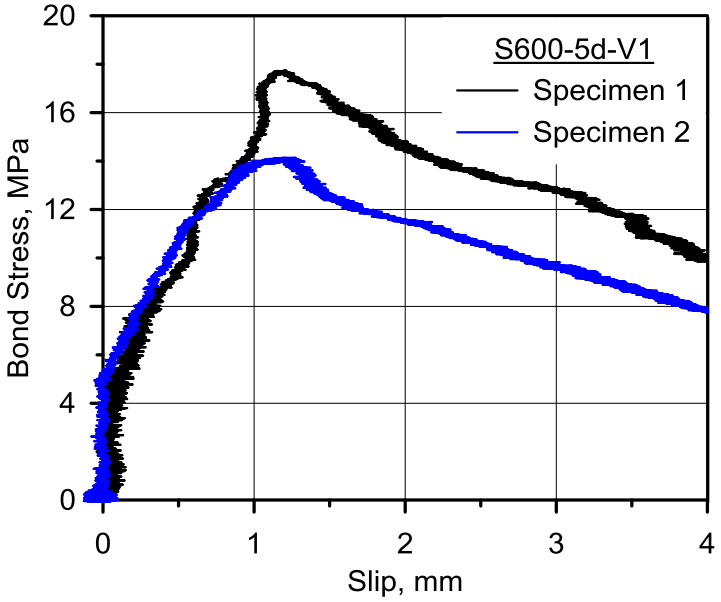


Figure 3.34 Bond stress vs. slip curve (1 m/s)

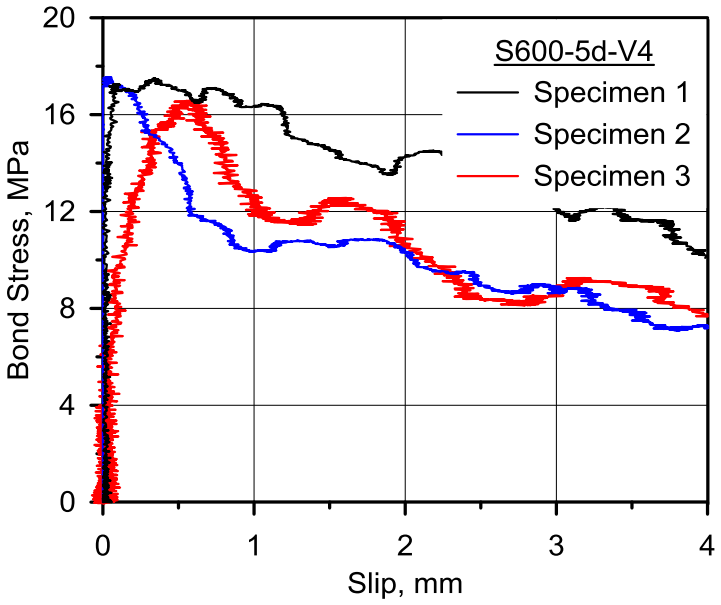


Figure 3.35 Bond stress vs. slip curve (4 m/s)

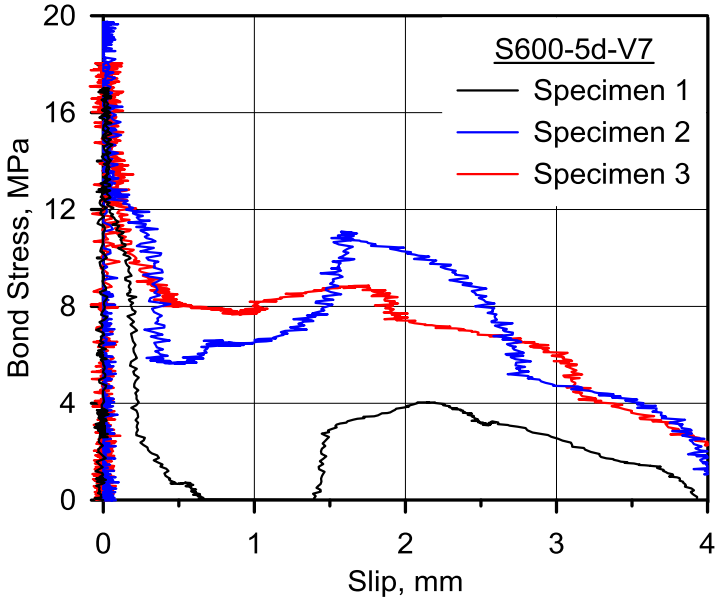


Figure 3.36 Bond stress vs. slip curve (7 m/s)

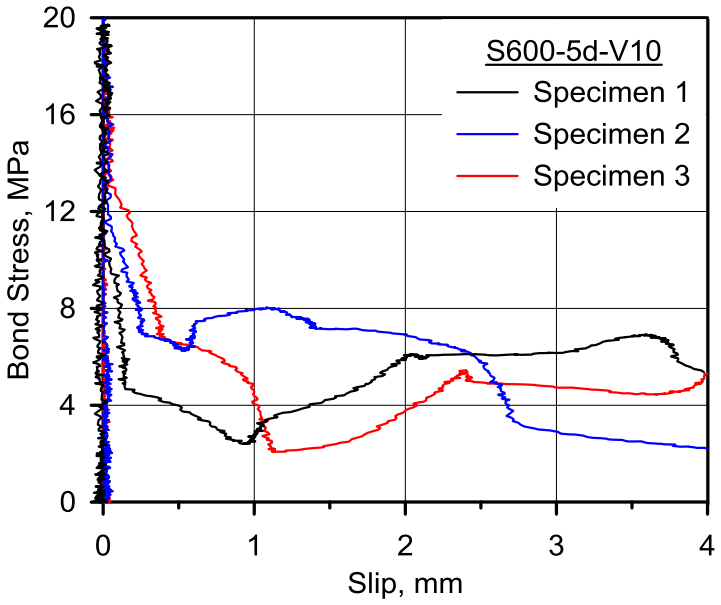


Figure 3.37 Bond stress vs. slip curve (10 m/s)

Table 3.7 Main pull-out test result

Specimen		ε_2	τ_{max} (MPa)	DIF_b	$\dot{\varepsilon}$ (s^{-1})
Static	1	0.000822	8.19	-	5.87e-6
	2	0.000899	8.96		5.99e-6
	3	0.00132	13.18		6.12e-6
1m/s	1	0.00178	17.75	1.76	0.31
	2	0.00142	14.14	1.40	0.25
4m/s	1	0.00176	17.51	1.73	2.00
	2	0.00176	17.54	1.73	2.35
	3	0.00166	16.57	1.64	1.03
7m/s	1	0.00171	17.01	1.68	5.03
	2	0.00198	19.75	1.95	3.41
	3	0.00181	18.05	1.79	2.30
10m/s	1	0.00198	19.72	1.95	4.21
	2	0.00207	20.60	2.04	3.39
	3	0.00191	19.04	1.88	2.48

3.4 Suggestion for bond DIF

Bond DIF from the test data is plotted with black dots in figure 3.38, and with the regression analysis the bond DIF is suggested along the strain rate based on the test data. It was constrained to be 1 at strain rate of static test result as highlighted with orange dashed circle in figure 3.38. It was found that the bond increases as the strain rate is getting bigger.

$$DIF_b = \left(\frac{\dot{\varepsilon}_{dynamic}}{\dot{\varepsilon}_{static}} \right)^{k_1} \tag{3.5}$$

$$k_1 = 0.0457$$
$$\dot{\varepsilon}_{static} = 5.87 \times 10^{-6}\ \text{s}^{-1} \tag{3.6}$$

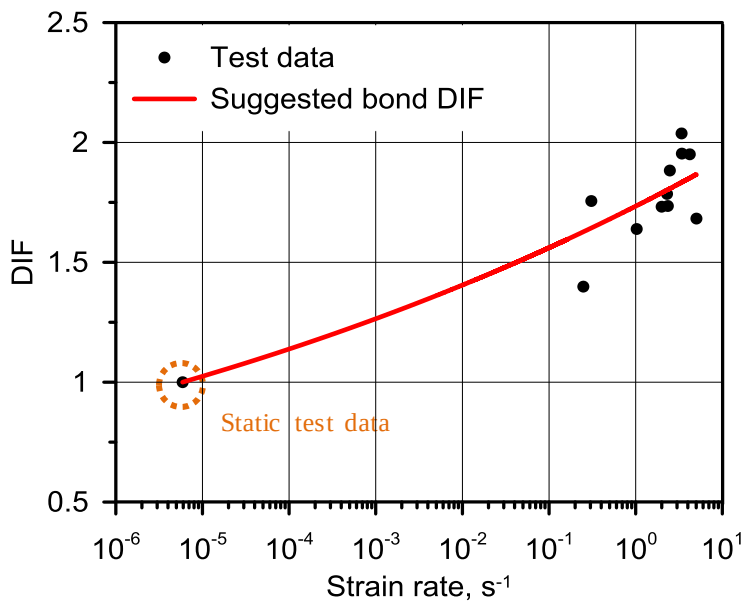


Figure 3.38 Proposed and representative DIF_b

4. Evaluation of safety of development length design

As mentioned in introduction chapter, one of the main objectives in this study is to evaluate the safety of current development length design. If the dynamic effect is considered in development length design, the bond DIF and rebar yield strength DIF is placed in denominator and nominator in development length design equation, respectively. In this chapter, therefore, the proposed bond DIF was compared with rebar yield strength DIF.

4.1 DIF of reinforcing steel yield strength

For DIF of rebar yield strength to be compared with suggest bond DIF in this study the Malvar formula was used. It was suggested based on 222 existing experimental data in 1998, and has advantages to be able to evaluate DIF in various yield strength range, 290 – 710 MPa, and strain rate range, 10^{-4} – $10s^{-1}$. Currently, it is adopted as rebar DIF model in fib MC2010, ACI370R-14 and UFC 3-340-02. For the rebar yield strength term in formula, the actual f_y value from rebar tensile test is used.

$$DIF_s = \left(\frac{\dot{\varepsilon}_{dynamic}}{10^{-4}} \right)^{0.074-0.040\frac{f_y}{414}} \quad (4.1)$$

$$DIF_u = \left(\frac{\dot{\varepsilon}_{dynamic}}{10^{-4}} \right)^{0.019-0.009\frac{f_y}{414}} \quad (4.2)$$

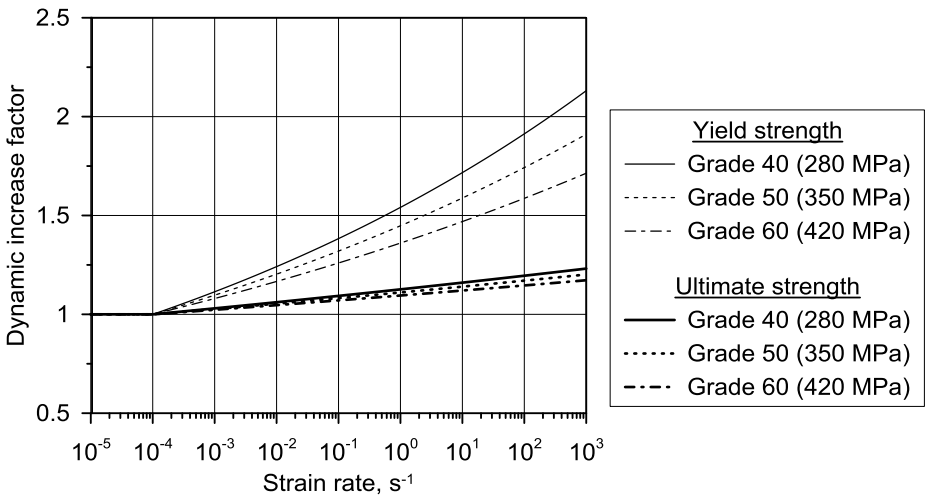


Figure 4.1 Reinforcing steel DIF from Malvar formula

4.2 Development length design check

4.2.1 Comparison between DIF_b and DIF_s

In figure 4.2 and 4.3, DIF_b and DIF_s are presented along the same strain rate range. The black dots, red, green, dashed-blue lines are test data, suggested bond DIF, rebar yield strength DIF for S400 and S600, respectively. It was found that bond DIF is bigger than DIF of rebar yield strength in test performed range, and the width of increase is getting larger as the strain rate is higher.

In bond DIF equation the denominator refers the strain rate from the static pull-out test, which was constrained to be 1 for bond DIF. As shown in figures below, the gap between the suggested bond DIF and rebar yield strength DIF is getting bigger as the rebar type changed from S400 to S600.

$$DIF_b = \left(\frac{\dot{\varepsilon}_{dynamic}}{5.87 \times 10^{-6}} \right)^{0.0457} \tag{4.3}$$

$$DIF_s = \left(\frac{\dot{\varepsilon}_{dynamic}}{10^{-4}} \right)^{0.074 - 0.040 \frac{f_y}{414}} \tag{4.4}$$

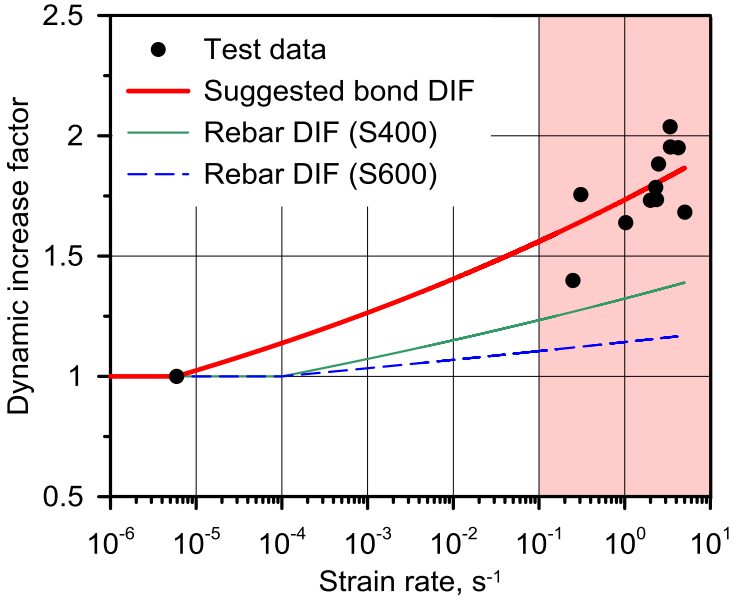


Figure 4.2 DIF_b and DIF_s comparison (all range)

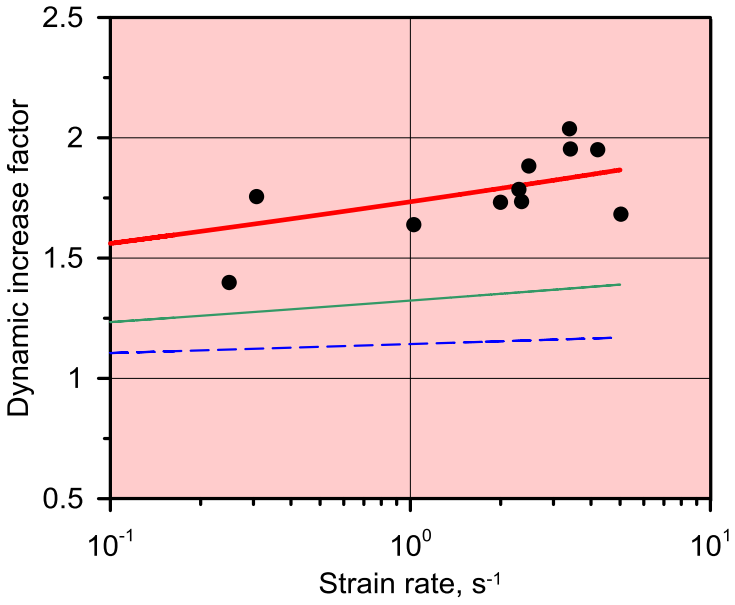


Figure 4.3 DIF_b and DIF_s comparison (10^{-1} to 10)

It was introduced in previous chapter that the development length would be affected by the ratio DIF_s/DIF_b when the dynamic effect is considered as equation below. In figure 4.4, by plotting DIF_s/DIF_b versus strain rate reducible ratio for current development length is calculated.

$$l_{dd} = \left(\frac{DIF_s}{DIF_b} \right) l_d \tag{4.5}$$

As a result, it could clearly be said that the needed development length regarding dynamic effect is shorter than current design method. To be specific, when the rebar strain rate is $1s^{-1}$, it was reducible with 20-30%, so it was found that the static state is dominant in the development length design.

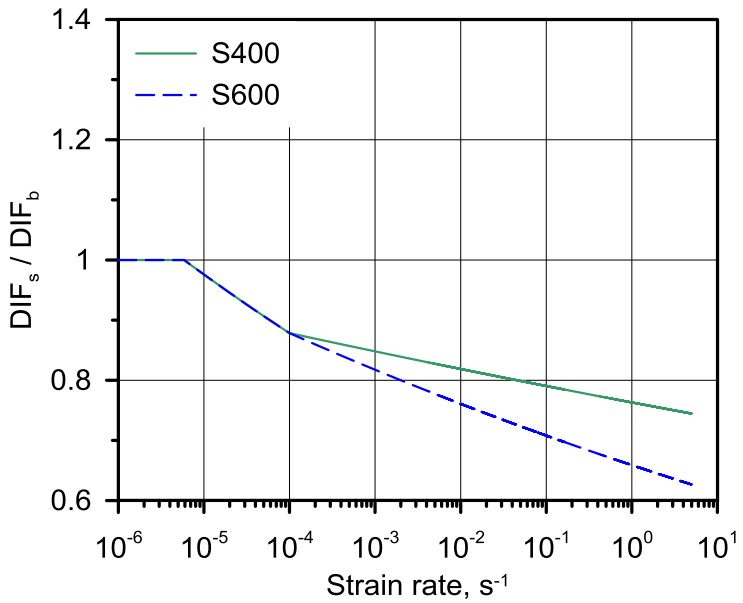


Figure 4.4 Reduction factor on development length in dynamic effect

4.2.2 The applicable range of the discussion

It was concluded previously that the dynamic effect is do not needed to be consider for development length design, but this is limited in the test performed range. Therefore, it would be said conclusions above in this study is valid in concrete structure with following conditions. First one is reinforcing steel strain rate. The test in this study was done in up to rebar strain rate $5s^{-1}$.

And the conclusion of this study is valid in concrete compressive strength under 25MPa. This is because the DIF_b is reversely proportional to concrete compressive strength according to previous studies. So, the ratio DIF_s/DIF_b might decreases when the concrete compressive strength is smaller than 25MPa.

Last one is reinforcing steel yield strength. Dynamic effect could be negligible in concrete structure with reinforcing steel that has over 400MPa of yield strength. As described in Malvar formula in figure 4.1, the DIF of rebar yield strength is reversely proportional to rebar yield strength, so the ratio DIF_s/DIF_b will be decrease when the reinforcing steel has yield strength over 400MPa.

5. Conclusions

In this study, the main generated issue was about consideration of dynamic effect on development length design. Currently it was found that no design codes or guidelines consider dynamic loadings for development length design. However, it was assumed if dynamic increase factor is regarded on DIF on bond and rebar yield strength, the needed development length could be affected because DIF_b and DIF_s are placed in denominator and nominator of development length design equation from ACI 318 and Eurocode 2, respectively. By literature review, it was determined new bond DIF should be suggested using test data showing pull-out failure mode only and the test technique should be constant in static and dynamic test.

Therefore, at first, pull-out test using the constant technique in static and dynamic state was performed to suggest bond DIF. All of specimens in main pull-out test shows pull-out failure mode, and based on those test data new bond DIF was suggested with regression analysis. The DIF of the rebar yield strength, which was compared with the suggested bond DIF was Malvar formula because it is valid in various rebar yield strength and strain rate range. As a result of comparison, it was found that the DIF_b is bigger than DIF_s in all test performed strain rate range, meaning that the dynamic effect does not needed to be considered in development length design in concrete structures with following conditions.

1. Reinforcing steel strain rate is lower than $5s^{-1}$

2. The concrete compressive strength is smaller than 25MPa

3. The yield strength of reinforcing steel is bigger than 400MPa

This is because, at first, the test in this study was performed within rebar strain rate lower than $5s^{-1}$. As the DIF_b and DIF_s are reversely proportional to concrete compressive strength and rebar yield strength, respectively, the DIF_s/DIF_b ratio might decrease as concrete compressive strength is smaller than 25MPa and rebar yield strength is bigger than 400MPa.

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국문초록

극한 하중하에서의
콘크리트와 철근의 부착 거동

이 현 송

과거에 비해 대형화가 진행되고 있는 근래의 철근 콘크리트 구조물은 그 크기에 비례하여 극한 하중에 의한 잠재적 위험성 또한 커지고 있다. 차량, 선박, 항공기 충돌, 폭발, 지진, 쓰나미 등 극한 하중은 일반적으로 정적 하중과 비교하여 높은 변형 속도가 작용하게 된다. 특히, 철근 콘크리트 교각이나 주탑의 경우, 이러한 동적 하중이 구조물의 하부에 발생할 가능성이 크게 된다. 이때 정적 하중 상황과 비교하여 동적 하중 작용 시에는 콘크리트나 철근의 재료 특성이 변하게 되므로, 그 둘 사이의 부착 거동 또한 조사되어야 한다.

이때 위에 말한 구조물의 하부는 기둥과 기초 사이에 접합부가 존재하게 되고, 이러한 부분은 구조물 전체로 보았을 때 비교적 취약부에 해당하게 된다. 하여 이러한 부분은 충분한 철근 정착 길이를 제공하는 방식으로 설계가 되고있고, 설계식으로는 ACI 318 과 Eurocode 2 에서 제시하는 식이 있다. 각 식의 분자는 철근

항복 강도 그리고 분모는 철근 콘크리트의 부착 강도를 고려하기 위한 항이 들어가게 된다. 이때 그 두 항에 동적 효과를 고려하여 동적증가계수를 적용하게 될 시, 만약 부착 강도의 동적증가계수가 철근 항복 강도에 대한 동적증가계수보다 작을 경우, 동적 상황에서의 필요 철근 정착 길이가 정적 상황에서의 것보다 크게 된다. 이는 정적 하중 상황만을 고려하여 설계된 철근 콘크리트 구조물에 동적 하중 작용 시 적절하지 못한 부착 파괴가 발생할 수 있다는 뜻이 된다.

하지만, 현재 어떠한 설계 기준이나 가이드 라인에서 철근 정착 길이에 대하여 동적 효과를 고려하고 있지 않아 이에 대해 검토가 필요하다고 판단하였다. 또한 현재 부착 강도에 대한 적절한 동적증가계수 모델이 없고, 풀 아웃 파괴 모드를 보이는 동적 풀 아웃 실험 데이터 수 또한 많이 부족한 상황임을 확인하였다. 그러므로, 본 연구는 정적 및 동적 실험에 동일한 실험 기법을 사용하여 모든 시편에 대하여 풀 아웃 파괴 모드를 보이는 실험 데이터로 부착 강도에 대한 동적증가계수 모델을 제안하고, 제안된 모델과 기존 철근 항복 강도에 대한 동적증가계수를 비교하여 현행 철근 정착 길이 설계식의 적정성 평가를 하고자 하였다.

먼저 풀 아웃 실험 시 풀 아웃 파괴 모드를 보장하기 위하여 예비 실험을 통하여 본 실험에서 쓰일 시편의 재원을 결정하였다. 풀 아웃 실험에 사용된 철근의 인장 실험 결과값과 철근 변형률 게이지에서 얻어진 값으로 부착 강도를 계산하였고, 변형률 속도는

변형률이 없을 때와 최대값일 때의 기울기로 얻어졌다. 실험 수행 후 변형률 속도에 따라 제안된 부착 강도의 동적증가계수와 Malvar 제안한 철근 항복 강도에 대한 동적증가계수를 비교해 보았다. 결과적으로 본 연구에서 수행된 모든 변형률 속도 구간에 대하여 부착 강도의 동적증가계수가 철근 항복 강도에 대한 동적 증가계수보다 큰 것으로 나타나, 철근 정착 길이 설계 시 동적 효과를 고려하지 않아도 된다는 결론에 이르게 되었다.

하지만, 위의 결론은 본 실험이 수행된 범위 내에서만 쓰일 수 있는 결론으로, 세부적으로는 철근 변형률 속도 $5s^{-1}$ 이하, 콘크리트 압축 강도 25MPa 이하, 그리고 철근 항복 강도 400MPa 이상인 철근 콘크리트 구조물에 대해서 적용이 가능하다. 하여, 현재 일반적인 철근 콘크리트 구조물에 적용하기 위해서는 높은 콘크리트 압축강도에 대하여 실험적 검증이 필요하다고 판단된다.

주요어: 풀아웃 실험, 철근 정착 길이, 부착 강도, 동적증가계수, 변형속도

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