Experiment Setup

This study intends to investigate the bonding behavior of reinforcing bars with impaired quality of adhesion and its impact to the flexural strength of a beam using flexural load experiment on a reinforced concrete beam with spliced reinforcing bars. The factors to the impairment of adhesive quality considered in this experiment are: the surface of reinforcing bars is coated with grease, the surface of reinforcing bars is coated with epoxy, and the newly poured concrete is violently disturbed after initial setting and before final setting.

The design setup of loading test mainly comes from the idea of experiment design done by Chinn; Ferguson and Thompson using beams subjected to flexural loads to investigate the bond strength in the splices of reinforcing bars when a splitting failure occurs. The bending deflection of beam puts the tension reinforcement in stress, so the bonding stress occurs along the surface of reinforcing bars between reinforcing bars and concrete. This bonding stress is responsible for the transfer of loads between concrete and reinforcing bars. Only with sufficient bond strength should both concrete and reinforcing bars become a complete composite structure to resist external loading by providing overall strength. The test mode of this experiment is close to the loading conditions of bonding in real structural members, and also is the test method that is most commonly used for evaluating reinforcing bar splices and the development length. Therefore, this experiment intends to obtain the knowledge of the bonding behavior of reinforcing bars in the case of insufficient splice length using the concrete beams under flexural loading test. The setting of experiment loads is to divide the beam specimen into shear zone and pure bending zone, as shown in Fig. 1. The splices are placed in pure bending zone to test the bond strength while the tension surface is allowed to develop at the top for the ease of description and observation on cracks.

Based on the different factors for the surface conditions of reinforcing bars, 14 beam specimens incorporating spliced reinforcing bars are prepared, and the size of specimens and the arrangement of reinforcing bars are shown in Fig. 2. In those specimens, 10 specimens are kept undisturbed and 4 are vibrated. The beams are 280cm long, 30cm wide and 25cm high. The main reinforcing bars in the tension zone are all #8 bars (the reinforcing bars in one of the specimens are replaced with steel round bars of the same nominal diameter), and those in compression zone are #4 bars. The thickness of concrete cover is 4cm all around. The splices of the reinforcing bars at tension side are located in the pure bending zone at the middle of the beams. To prevent shear failure from occurring during the flexural load experiment, the shear zone at the outside of supported ends is installed with stirrups made of #3 bars at the intervals of 8cm. Moreover, while the specimens were being poured, several cylindrical concrete specimens and bending specimens are produced to obtain the basic material properties of concrete for the related studies.

In the undisturbed specimens, for the purpose of simulating that there are changes in the interface of reinforcing bars and concrete impacting the quality of adhesion, the surface of splices is coated semi-solid grease and epoxy. To compare the possible influence due to different bonding conditions, the length of reinforcing bar splices and the arrangement of stirrups within the splice zone are made different purposefully.

The following principle is introduced for the designation of specimen design: the first number represents the surface properties of reinforcing bars, for which N means the normal conditions without treatment, E is that the surface of reinforcing bars is coated with epoxy of 0.1~0.13cm thick, O is that the surface reinforcing bars is coated with semi-solid grease of 0.1~0.2cm thick, and P is that the reinforcing bars are replaced with steel round bars with a diameter of 2.5cm; the second number corresponds to the splice length of reinforcing bars, for which 20 is the splice length of 20cm and 30 is of 30cm; the third number tells the condition of confinement, for which NC is no stirrup confinement in the splice zone, and C stands for the confinement of #3 stirrups placed in the splice zone at equal intervals (10cm); and the fourth number is the serial number indicating the number of specimens under the same design conditions. The details of specimen setup are shown in Table 1.

To facilitate the impact to the impaired quality of adhesion at the interface of reinforcing bars and the concrete caused by the severe disturbance on the newly poured concrete from the simulation of specimens, 8 linearly elastic springs with a spring constant of k =193.7*N/cm* and the maximum design elongation of more than 10cm are adopted in the lab, and a steel plate of 170cm L x 70cm W x 2.2cm T and weighing 255kg is added to establish a platform on which free vibration can be generated. Measured with an accelerometer, the free vibration frequency of the vibration platform assembly is obtained and shown in Fig. 3. The primary frequency of vibration is 3.66Hz, and the period of vibration is determined to 0.27 second after conversion. Later, the newly poured concrete beam specimens are placed along with the wood formwork on the vibration platform after the initial setting and before final setting, and roller bearings are placed at proper locations under the formwork, allowing flexural vibration occurring to the specimens during the vibration. Finally, a psudo-dynamic tester is used to force the platform to generate an upward initial displacement and the entire setup is released instantly to allow the up-and-down free vibration of the assembly of specimens and platform to a natural stop. The experiment setup is shown in Fig. 4.

In the setup of the specimens put to vibration, 3 of the beam specimens are designed with the same reinforcing bar arrangement as in the normal specimen (N-30-NC-1) that is not put to vibration, and the splice length is 30cm and no stirrup is placed in splice zone; the 4th specimen has the same reinforcing bar arrangement as in the normal specimen (N-30-NC-1) and the splice length is 30cm, except that 3 #3 stirrups are placed in the splice zone with equal intervals (10cm).

The following principle is introduced for the designation of specimen design: the first number is S, representing that the beam is put to vibration; the second number indicates the support distance when the beam in placed on the platform, for which A is that the support distance is 100cm and B 150cm; the third number tells the levels of vibration, including 3 levels, 1, 2 and 3; and the fourth number corresponds to the condition of confinement, for which C means the confinement of stirrups is present, and no number is placed at this position if there is no confinement of stirrups. The details of specimen setup and the historic records of vibration measured are shown in Table 2.

Bond Strength

The bond strength studied in this experiment is the bond stress when the splitting failure occurs before the reinforcing bars yield, and the definition of bond strength is the same as that used by the researchers that was determined in the *OJB* model.

The calculation of bond strength at failure assumes that the bond stress is evenly distributed along the length of splice. This assumption has been confirmed in the observation of the experiment performed by Olsen. From the equilibrium of forces, i.e. the forces in the reinforcing bars are transferred completely by the evenly distributed stress, the following equation is obtained:

$$A_s \cdot f_s = u \cdot \pi \cdot d_b \cdot L_s \tag{1}$$

Further, from eq. (1), the bond stress u is determined:

$$u = \frac{f_s \cdot d_b}{4 \cdot L_s} \tag{2}$$

In this experiment, the stress in the reinforcing bars (f_s) is calculated from the cross section, and the calculation process is: load (P) is measured when the beam is subjected to a flexural load, and multiplied by the distance (65cm) to obtain the bending moment acting on the cross section. Then, it is assumed that the plane remains unchanged before and after loading, the reinforcing bars and surrounding concrete have the same strain, and the stress-strain relation displays a linear pattern. Therefore, the stress of reinforcing bars (f_s) is determined using the following equation:

$$f_s = \frac{M}{A_s \cdot j \cdot d} \tag{3}$$

For an easy comparison of experiment results between different strengths of concrete, the "bond index" is generated in this study by dividing the bond stress with the square root of the concrete strength, as eq. (4) indicates:

$$B.I. = \frac{u}{\sqrt{f_c'}} \tag{4}$$

And the meantime, for the comparison between the specimens of different condition of adhesion, the B.I. of the specimens of which the surface of reinforcing bars is flawed is divided by the B.I. of the specimens with a normal bond under the same conditions to obtain "bond ratio".

The bond stress calculated using eq. (2) is analyzed under the following 2 circumstances: (1) during the experiment, the load is recorded when the first flexural crack is observed, and later the real load corresponding to the decrease of stiffness is found in the measurement data. The corresponding bond stress is called "bond stress of cracking"; (2) the bond stress corresponding to the ultimate load is designated as the "ultimate bond stress". Since the difference between bond stresses of cracking is insignificant, it is not easy to be identified in the load-deflection curve. Considering possible error of identification, only the corresponding bond indices are used to describe the behavior rather than going through the analysis of bond ratio. The calculation result is shown in Table 3. The ultimate load for the "ultimate bond stress" is specific enough to be used for calculating the changes in ultimate bond ratio, and the analysis result is summarized in Table 4. According to the difference of the adhesion on the surface of reinforcing bars, the following is the discussion on the changes in the bond stresses:

Specimens of N series

First, the experiment result of reinforcing bars with normal adhesion is verified using the equation suggested in the *OJB* model: for the specimens with no confinement of stirrups, the u_{OJB} is 5.53MPa, and the u_{test} obtained in the analysis of this experiment is 4.98MPa; for the specimens with no confinement of stirrups, the calculated u_{OJB} is 6.71MPa, and the average u_{test} obtained in the analysis of this experiment is 5.68MPa. It is clear that there exists difference between the above two, but the difference is acceptable providing that the equation of *OJB* model is an empirical one. It indicates that the concrete beams containing reinforcing bar splices that go through the flexural load experiment as set up in this study demonstrate the same behavior of bonds as the bond studies done by the predecessors under the splitting failure before the yielding of the reinforcing bars.

Further examining the experiment result, it shows that the average B.I. for the cracking load of the beam specimens without the confinement of stirrups is 1.04, and that for ultimate load is 2.43; the average B.I. for the cracking load of the beam specimens with the confinement of stirrups is 1.15 and that for ultimate load is 3.09. It is quite obvious that the ultimate bond stress is much higher in beam specimens with the confinement of stirrups than in those without, but there is not much influence in the initial bond stress of cracking.

Specimens of E series

When the reinforcing bars are coated in epoxy, the surface of the bars becomes smooth because of the coating, allowing changes in the adhesion, while the friction between the reinforcing bars and concrete reduces as well. Therefore, the bond strength is provided mostly by the bearing force, which means theoretically the bond strength is smaller that that of reinforcing bars without epoxy coating, i.e. the bond strength is factored down due to the smoothened surface of reinforcing bars.

The result from the experiment under cracking load shows: among the beam specimens with reinforcing bars coated in epoxy, the B.I. of those without the confinement of stirrups is 3.69, while that of those with the confinement is 0.91. Compared with the experiment result from reinforcing bars with normal adhesion, it is clear that the bond stress of cracking tends to drop under the influence of epoxy coating, and the trend of dropping is more significant in the specimens with the confinement of stirrups than in those without.

The result from the experiment under ultimate load shows: among the beam specimens with reinforcing bars coated in epoxy, the B.I. of those without the confinement of stirrups is 2.2, and the bond ratio corresponding to the ultimate bond stress is 0.9, i.e. the reduction in the ultimate bond stress is 10%; the B.I. of those with the confinement of stirrups is 2.73, and the bond ratio corresponding to the ultimate bond stress is 0.88, i.e. the reduction in the ultimate bond stress is 12%. It shows that the ultimate bond stress tends to drop under the influence of epoxy coating, while the confinement of stirrups improves the ultimate bond stress.

Specimens of O series

When the surface of reinforcing bars is coated with grease, it is impossible for concrete to create bonding with the reinforcing bars, and since grease serves as lubricant, it allows a considerable drop in the friction at the interface. Therefore, it is expected that the reduction of bond stress is more severe than in epoxy-coated specimens.

The result from the experiment under cracking load shows: among the beam specimens with reinforcing bars coated in grease, the B.I. of those without the confinement of stirrups is 0.72, while that of those with the confinement is 0.64. Thus, it is clear that the bond stress of cracking tends to drop under the influence of grease coating as well.

The result from the experiment under ultimate load shows: among the beam specimens with reinforcing bars coated in grease, the B.I. of those without the confinement of stirrups is 2.01, and the bond ratio corresponding to the ultimate bond stress is 0.83, i.e. the reduction in the ultimate bond stress is 17%; the B.I. of those with the confinement of stirrups is 2.38, and the bond ratio corresponding to the ultimate bond stress is 0.77, i.e. the reduction in the ultimate bond stress is 23%. Similarly, it shows that the ultimate bond stress tends to drop under the influence of grease coating, and the drop is more significant than in epoxy-coated specimens.

Specimens of S series

It is possible that voids take shape at the boundary between reinforcing bars and concrete or a weak plane is formed due to impairment of adhesive force if the newly poured concrete is subjected to violent vibrations after the initial setting and before the final setting. The degree of impairment depends on factors such as the initial time and the duration of vibration, and the energy of vibration, etc. In this study, only violent free vibration of large displacement is introduced to force the beam specimens to generate obvious flexural vibrations for demonstrating the influence of this magnitude of vibrations to the bond force.

The result from the experiment under cracking load shows: among the beam specimens subjected to vibrations, the B.I. of those without the confinement of stirrups is approximately 0.47~0.8, while that of those with the confinement is 0.38. Therefore, with or without the confinement of stirrups, there is an obvious drop in the bond stress of cracking for the newly poured reinforced concrete beam specimens subjected to the influence of violent vibrations.

The result from the experiment under ultimate load shows: among the beam specimens subjected to vibrations, the B.I. of those without the confinement of stirrups is approximately 1.86~2.15, and the bond ratio corresponding to the ultimate bond stress is around 0.77~0.88, i.e. the reduction in the ultimate bond stress is 12~23%; the B.I. of those with the confinement of stirrups is 2.91, and the bond ratio corresponding to the ultimate bond stress is 0.95, i.e. the reduction in the ultimate bond stress is 5%. Similarly, it shows that, for the newly poured reinforced concrete beam specimens, the ultimate bond stress indeed tends to drop under the influence of violent vibrations.

It is noticed that when there is no confinement of stirrups, the degree of reduction is close to that observed in specimens with grease-coated reinforcing bars, indicating large decrease in adhesive force and friction; however, the degree of reduction in specimens with the confinement of stirrups is not as significant. Therefore, it is safe to say that the influence of violent vibrations to the reduced ultimate bond stress is improved effectively with the confinement of stirrups. In addition, the most critical factor for the influence of vibration to bond force is the time when the vibrations start. It is observed that, if the vibrations start at 6 hours after the mixing of concrete (about when the initial setting starts), the reduction in the ultimate bond stress is merely 12%, despite that noticeable cracks have taken shape after the specimen has been given vibrations of enormous magnitude and pretty long period of time (S-B-3); as for the specimen where the vibrations start earlier (S-A-2), the reduction in the ultimate bond stress can drop as much as 23% even though there is no noticeable vibration crack on the surface, and it is even lower than that of specimens that have lost adhesive force and friction complete (O-30-NC-1). Thus it is evident that the time when the vibrations start is the major factor of influence.

Specimens of P series

The bond stress in the beam specimens with steel round bars as reinforcement comes mainly from the adhesive force and friction. When the specimens are subjected to ultimate stress, there is only relative slipping occurring between steel bars and concrete, and it is not easy to create splitting failure. Thus, whether or not there is sufficient confinement of stirrups does not impose much influence to the ultimate bond stress. Therefore, only one set of beam specimen is designed without the confinement of stirrups for investigation.

The result from the experiment shows: when subjected to cracking loads, the B.I. of the specimen reinforced with steel round bars is 1.36, and the bond ratio corresponding to the reinforcing bars with normal bond is 0.56, while the reduction in the ultimate bond stress is 44%, indicating that the ultimate bond stress is only a half of that of reinforcing bars. If taking the effect of stirrup confinement into account, the ratio could have dropped even further. It is quite clear that when subjected to ultimate stress, the ribs on the reinforcing bars are really the major source of bond stress.

Load – Deflection Curve

The load – deflection curve is the basic curve that describes the behaviors of beam specimens as a structure member. In this load – deflection curve, load is the average measured at the left and right load cells, and deflection is the relative displacement between the middle point and the loading points at the end of the beam. The load-deflection curves obtained from the flexural load experiment are plotted in Fig. 8 and 9 according to the difference of beam specimens with or without the confinement of stirrups in this experiment. In the figures, (P_{cr}) stands for the load at the time that cracks occur, and the ultimate load (P_u) is defined as the load measured when the splitting failure occurs. It is observed from the load – deflection curves that the relation between loads and deflections remains approximately linear before flexural cracks occur on the beam, and after cracks occur, the curve starts to bend slightly, indicating that the cracks lead to the softening of beam specimens, i.e. the stiffness decreases.

For the purpose of comparison, the load-deflection curves of the specimens with and without the confinement of stirrups are plotted together in Fig. 10. As shown in the figure, the deflection demonstrates a rapid increase and the load drops very quickly when reaching the ultimate bond stress; however, the drop of strength is slower with the confinement of stirrups, displaying the trend of more ductile failure; nevertheless, if the confinement of stirrups is absent, the degradation of strength accelerates, exhibiting the trend of brittle failure.

Fig. 11 provides the load-deflection curves of the surface of reinforcing bars under different conditions of adhesion. It is found in Fig. 11 that the initial stiffness is pretty close, but then the loads when the cracks occur may be somewhat different under the influence of changes in the conditions of adhesion. In the case that there is normal adhesion on the surface of reinforcing bars, the load at which the curve reaches the turning point of cracking is the highest; if the surface of reinforcing bars is coated with epoxy or grease, the load at which the curve reaches the turning point of cracking drops a little; however, if in the beam specimens of newly poured concrete that are subjected to violent vibrations, then the load at which the curve reaches the turning point of cracking drops even more. The cause is likely to be that there may have been some hairline cracks occurring in the concrete covers or voids at the interface between concrete and reinforcing bars while the specimens were subjected to violent vibrations. As for the beam specimen reinforced with steel round bars, the load at which the curve reaches the turning point of cracking is close to that of the specimens reinforced with epoxy or grease coated reinforcing bars, indicating that the steel round bars cannot incorporate themselves in the concrete as the ribbed reinforcing bars do to resist the cracking bending moment in a joint fashion.

After a turning point of crack occurs in a load-deflection curve, the trend of stiffness will be slightly different due to the difference in the adhesion conditions on the surface of reinforcing bars, but the difference is not significant since the contribution of adhesive force drops rapidly, even diminishes after there is relative displacement occurring between reinforcing bars and concrete, and only the bearing force of ribs and friction provide the resistance, in which the bearing force of ribs contributes more and the friction covers only fraction of it, against external loads. This conclusion can be verified from Fig. 11 that the stiffness of specimens with normal adhesion of reinforcing bars is a little greater than that of specimens with epoxy-coated reinforcing bars, and the stiffness of specimens with epoxy-coated reinforcing bars is slightly greater than that of specimens with grease-coated reinforcing bars. As for the specimen reinforced with steel round bars, since there is no contribution from the bearing force of the ribs, the stress will remain close to that strength after the friction contributes to the greatest, but the deflection will keep increasing.

CONCLUSIONS

According to the result of the experiment and analysis, the following conclusions can be summarized:

1. As the result of loading experiment shows, the ultimate bonding force in a specimen that has lost adhesion and friction completely may reach 80% of that in regular specimens (N series); that of the specimens with partial interface impairment falls between the above two.
2. The ultimate bond stress of a specimen of which the bonding force is provided solely by adhesion and friction without the contribution of rib bearing force can reach as much as 56% of that of a regular specimens, indicating that adhesion and friction forces can still play a crucial roll in the first half of loading stage. After adhesion is lost in regular specimens, the friction and bearing force of ribs will take over to provide for the bonding force.
3. The influence of vibrations to the bonding force is very significant in the case that there is no confinement of stirrups. Taking the specimens in this study as example, 5 hours after the vibrations has occurred to the newly poured concrete, the ultimate bond stress can be reduced as much as 23%, and that is much lower than that of a specimen that has lost both adhesion and friction completely.
4. For the beam specimens without the confinement of stirrups, they tend to display the trend of brittle failure due to apparent slipping when the reinforcing bars have reached the ultimate bonding strength if only the concrete provides the confinement strength. For the beam specimens with the confinement of stirrups, they tend to demonstrate the trend of ductile failure due to the increased confinement.