Bond Between SSTT Confined Concrete and Ribbed Steel Reinforcement Bar

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ABSTRACT

A study about bond strength of normal strength concrete (NSC) and Steel Strap Confining Technique (SSTT) confined NSC was presented. A series of 8 specimens pull-out test were carried out to investigate the bond strength of short embedment ($5D_b$) in SSTT confined NSC. The concrete compressive strength was about 45 MPa meanwhile the 12mm diameter reinforcement tensile strength was about 500 MPa were used in the pull-out specimens. In order to determine the effects of lateral confinement pressure of steel strapping, three groups of different steel strap gap distance pull-out test were conducted and compared with control specimens and previous theoretical bond stress equation. It was found that SS-B pull-out specimen exhibited highest bond strength and about 40 percent higher compared with Cont-B specimen as lowest bond strength pull-out specimen in this study.

Keywords: Bond strength; Lateral confinement pressure; Steel strap; Confinement method; Active confinement

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INTRODUCTION

Steel Strap Tensioning Technique (SSTT) is one of the confinement methods has been proven significantly increase concrete strength and ductility (Moghaddam *et. al.,* 2008; Ma *et al.,* 2014a, 2014b, 2016a, 2016b, 2016c, 2016d). Confinement method separated into active and passive confinement. Zawawi, 2013 states that active confinement comes from direct action loading where this type of confinement is not dependent on the lateral strain of concrete to confining concrete. Furthermore, active confining methods are giving full lateral confining pressure before concrete dilation. Meanwhile, passive confinement method is totally dependent on concrete strain and dilation. The lateral confining pressure begins as concrete expanding due to expansion of concrete core inside transverse reinforcement.

The advantages of the usage of high strength reinforcement in reinforced concrete can give a stronger structural member with reduced dead load. A related investigation regarding bond behaviour of SSTT confined concrete and ribbed steel reinforcement bar is necessary for design rules. This paper is a step in this direction.

One of the most commonly used local bond-slip models is pull-out test conducted with reinforcement short embedment length. In this case, the reinforcement bar slipped and experienced strain well under the yield steel strain. In order to investigate the local bond behaviour of SSTT confined concrete, 8 pull-out specimens with concrete compressive strength about 35 MPa and tensile steel greater than 500 MPA were conducted with different volumetric confining ratio.

THEORETICAL MODEL

The bond inside reinforced concrete is made up of chemical adhesion, friction and mechanical interlocking (Magnusson, 2000). For plain bar, the bond resistance is only made up by adhesion and friction between bar and surrounding concrete. In ribbed bar, mechanical interlocking between

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reinforcement and concrete is the main contributor leads toward bond strength and bonding effectiveness in reinforced concrete (Eligehausen *et. at.*, 1983; ACI committee 408). The transfer of tensile force from reinforcement into concrete causes tangential stress along reinforcement and concrete contact surface. The stress acting parallel with reinforcement bar and concrete is called bond stress. In order for reinforced concrete to serve well, the bond behaviour between reinforcement and concrete must be function effectively. Fig 1 depicts the equilibrium condition for bond stress, τ, expression.

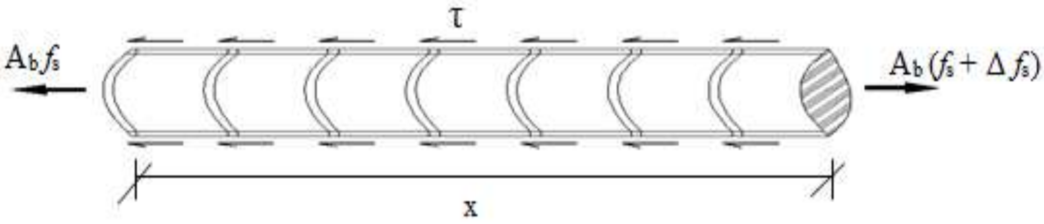

Figure 1. Equilibrium conditions of reinforcement due to external force.

$$\tau(\pi d_b x) = A_b\,(f_s + \Delta f_s) - A_b f_s \qquad (1)$$

Then,

$$\tau = \frac{A_b\,\Delta f_s}{\pi d_b x} = \frac{d_b \Delta f_s}{4x} \qquad (2)$$

Where A_b is reinforcement bar area, d_b is the reinforcement bar diameter and f_s is the stress in reinforcement bar.

For uniform bond, stress resistance or maximum bond stress can be simplified as:

$$\tau = \frac{P_{max}}{\pi d L_d} \qquad (3)$$

Where P_{max} is the maximum pull-out load, d is diameter of the reinforcement bar and L_d is the embedded reinforcement length.

Many researches have proposed bond equation of ribbed reinforcement and concrete. Darwin *et. al.*, 1992 proposed a modified equation (SI) of bond strength as below:

$$\tau = 0.083045\sqrt{f'_c}\left[\left(1.06 + 2.12\,\frac{c}{d_b}\right)\left(0.92 + \ 0.08\,\frac{C^*_{max}}{C_{min}}\right) + 75\,\frac{d_b}{L_b}\right]$$

Where C= min (C_x, C_y, C_s/2) and C^*_{max} = max [$\min\left(C_x, \frac{C_y}{2}\right)$, C_y] ; C_x is side cover, C_y is bottom cover and C_s is spacing between bars.

Besides that, Hadi (2008) proposed bond strength formula quiet similar to Darwin's equation:

$$\tau = 0.083045\sqrt{f'_c}\left[22.8 - 0.208\frac{c}{d_b} - 38.212\frac{d_b}{L_b}\right]$$

Where f'_c is concrete compressive strength, c is concrete cover, L_b is embedment length and d_b is reinforcement diameter.

PULL-OUT TEST SPECIMEN

The pull-out specimens were designed using concrete compressive strength about 35 MPa with reinforcement tensile strength with 12 mm nominal diameter. Before casting, the Y12 reinforcement and steel strap were tested for the tensile strength at the Structure and Material Laboratory, Universiti Teknologi Malaysia (UTM). The tensile test experimental results are shown in Table 1 and Table 2. Meanwhile, the average compressive strength of concrete is about 45 MPa.

Table 1. Y12 tensile strength data

Reinforcement Bar	Diameter, mm	Yield Strength, MPa	Ultimate Strength, MPa	Modulus of Elasticity, GPa
Ribbed bar	Y12	526	621	190

Table 2. Steel strap tensile strength data

Steel Strap	Size, mm	Yield Strength, MPa	Ultimate Strength, MPa	Modulus of Elasticity, GPa
-	15 x 0.04	625	788	202

The cylindrical PVC mould of 150 mm diameter with 300 mm height was used to produce the pull-out specimens. High strength steel reinforcement with 720 mm length was fixed concentrically in the mould by wooden framed mould and tightened well to wooden mould as shown in Fig 2. The reinforcement embedment length was designed for $5d_b$ which is equal to 60 mm and PVC tube was used to cover the reinforcement bar. During casting, concrete was poured in three layers and compacted by mechanical penetrating vibrator. The moulds were kept until age day 7 of casting day. After the mould was removed, the specimens were cured using Burnlap cloth until age day 28.

Figure 2. Pull-out test mould.

Three days before pull-out test, the specimens are confined with steel strap using pneumatic tensioner. The steel strap volumetric ratio was designed into: a) single layer steel strap with no spacing; b) single layer steel strap with 10mm spacing and c) single layer steel strap with 20mm spacing as shown in Fig 3. The pull-out specimens were divided into four groups based on gap distance between steel strapping (control denoted as Cont, no gap denoted as SS, 10mm gap denoted as SS10 and 20 mm gap denoted as SS20). These specimens were tested with 2 specimens each group for consistency and compared with plain pull-out specimen.

(a) (b) (c)

Figure 3. Pull-out specimens with: a) single layer steel strap with no spacing; b) single layer steel strap with 10mm spacing and c) single layer steel strap with 20mm spacing

TEST SETUP AND PROCEDURE

Pull-out test arrangements are shown in Fig 4. The pull-out specimens were tested using Universal Testing Machine Dartec at Structure and Material Laboratory DO4, Universiti Teknologi Malaysia (UTM). The hollow hydraulic machine has a maximum loading of 45 tons (450 kN). The pull-out test was conducted according to RILEM/ CEB- FIP guideline procedure with 1.2 mm/min rate of strain mode control. The choice of this procedure is mostly due to shape and size of specimens. The adaptions of cylindrical instead of cubic specimens were to provide axisymmetric cover to reinforcement bar and avoiding disturbance of other parameters besides those under analysis. The sample was secured on hollow ring holder and a metal plate was placed on top the specimen to retain the sample for pull-out test as shown in Fig 4. The specimens were kept in a frame which hanged from the actuator. A straight iron was attached with reinforcement and connected with LVDT for slip measurement purposes. The load cell and LVDT were connected to data logger which continuously recorded the respective reading. Two identical tests of each specimens were carried out to have a minimal statistical basis.

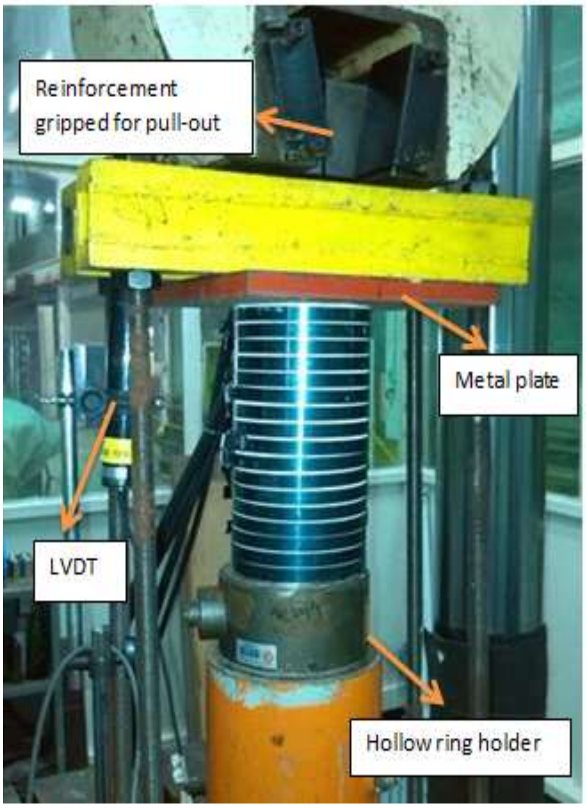

Figure 4. Specimen arrangement for pull-out test

RESULT AND DISCUSSION

Eight pull-out specimens were tested for bond strength determination of different spacing of single layer of steel strapping. The bond stresses were calculated using equation (3) and compared with theoretical equations proposed by Darwin *et. al.* (1992) and Hadi (2008). All these bond strength results are presented in Table 3 and Fig 5.

Table 3. Summary of pull-out test results

Spec.	Bar dia., mm	Embedded length, mm	Maximum force, P_{max} (kN)	Measured bond stress, τ (MPa)	Theoretical Bond stress, τ	
					Darwin (MPa)	Hadi (MPa)
Cont-A	12	60	41	18.123	15.4806	7.7198
Cont-B	12	60	36	15.913	15.4806	7.7198
SS-A	12	60	50	22.101	15.4806	7.7198
SS-B	12	60	60	26.522	15.4806	7.7198
SS10-A	12	60	48	21.217	15.4806	7.7198
SS10-B	12	60	54	23.870	15.4806	7.7198
SS20-A	12	60	52	22.989	15.4806	7.7198
SS20-B	12	60	49	21.663	15.4806	7.7198

The table shows that the more the steel strap confining the concrete; the higher the bond strength. Specimen SS-B indicated highest bond strength among other specimens with 26.522 MPa while Cont-B exhibited lowest bond strength with 15.913 MPa about 40 percent differences between both specimens. Besides that, SS-B specimen exhibited about 41 percent and 71 percent higher than the theoretical bond stress proposed by Darwin *et al.* (1992) and Hadi (2008) respectively. This is due to presents of lateral confining pressure occurred on SS-B specimen. As the reinforcement is pulled out from concrete, the lateral pressure prevented the concrete core from expanding and tightening the concrete core. The effects of lateral pressure kept the concrete core from behaving lateral strain; hence it will increase the concrete strength and preventing the reinforcement bar to be pulled out from the specimen (Torre-Casanova *et al.*, 2013).

Besides that, bond strength of SS specimen is about 7.5 percent and 8.5 percent higher than SS10 and SS20 specimen. This happened because Cont. specimen was confined under full range of external lateral confinement with no gaps between steel strapping. Since the SS specimen was fully confined, this leads to better concrete core restrain than SS10 and SS20 specimen. In this study, only pull-out failure (Fig 5) as mode of failure was observed in all specimens since only short embedment length is considered. No other types of failure such splitting and steel rupture failures were observed during experiment. The bond strength is mainly controlled by concrete cover and lateral confining pressure provided by steel strapping around the concrete.

Figure 5. Reinforcement bar slip of pull-out failure

Fig 6 illustrated the bond strength of pull-out specimens respectively. The average bond strength of pull-out specimen increased in ascending order from control, SS20, SS10 until SS specimen. The average bond strength recorded for SS specimen was about 30 percent higher than average bond strength recorded for control specimen. Meanwhile, the average bond strength exhibited by SS20 and SS10 was about 23 percent and 25 percent higher than control specimen respectively. As confining level of steel strapping increased, the bond strength of pull-out test recorded was also increased. The presents of steel strapping as external lateral confinement was proved to be efficient in providing lateral pre-tensioned stress in restricting dilation of concrete core. This external lateral confining pressure gives confinement stresses inside concrete core which significantly increased the bonding interaction between reinforcement bar and surrounding concrete (Torre-Casanova *et al.*, 2013).

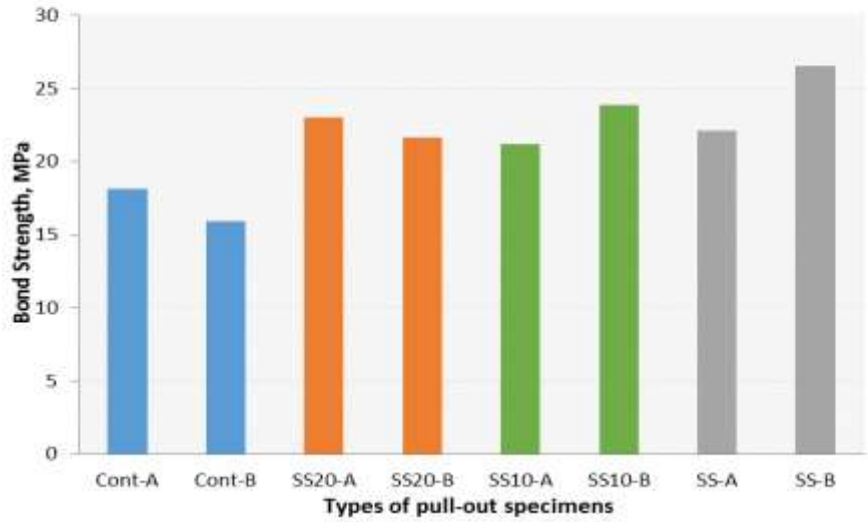

Figure 6. Bond strength of pull-out specimens

Fig 7 shows the bond strength against bar slip relationship in this study. It clearly shows that Cont. specimen was exhibited the lowest bond strength and shortest bar slip meanwhile SS specimen showed the highest bond strength and longest bar slip recorded follows by SS10 and SS20 specimen in this pull-out series. From the pull-out results, it is proven that lateral confinement pressure is significantly increased bond strength and reinforcement bar slip in this study. The higher the number of steel strap confining the concrete, the bigger the bond strength of pull-out test results.

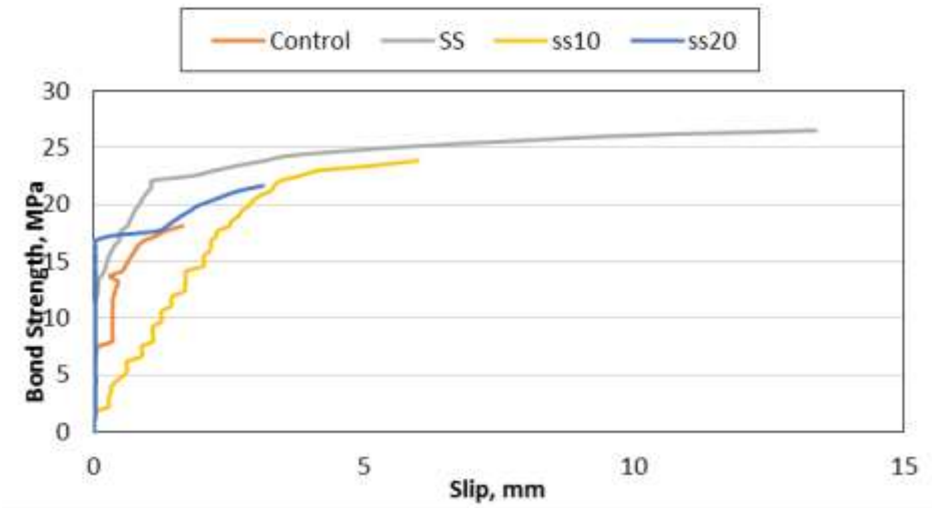

Figure 7. Bond strength-slip relationship

CONCLUSION

Based on this pull-out series of 8 specimens of short embedment, it can be concluded that pull-out specimen with higher number of steel strapping has greater bond strength and exhibited longer reinforcement bar slip. The maximum bond strength of this study was recorded on SS-B specimen while lowest bond strength was in Cont-B specimen with about 40 percent differences in bond strength between the specimens.

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