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PREDICTION OF ANALYTICAL BOND STRENGTH OF LAP SPLICES IN TENSION

G. APPA RAO[*], S. PRIYANKA REDDY[*] AND R. ELIGEHAUSEN[†]

[*]Department of Civil Engineering,
Indian Institute of Technology Madras, Chennai – 600036, India.
email. garao@iitm.ac.in.

[†]Department of Fastening Technology, University of Stuttgart, Germany.
email eligehausen@gmx.de.

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Abstract: A significant experimental and analytical evidence of anchorage bond of ribbed bars under monotonic and cyclic loading has been generated from various sources. While additional test data have resulted in an increase in the accuracy of current statistical approaches, splice strength remains not fully understood. A number of factors such as type of rebar and concrete, state of stress in materials, concrete cover, spacing of rebars, number of layers of rebars, direction of casting, position of bar, Poisson's effect, diameter of rebar, cyclic loading, bar geometry and rib geometry influence the bond strength. The objective is to develop a model that predicts the bond strength incorporating all influencing parameters for design applications along with size effect of rebar. Mechanics based standard splice strength model has been proposed from a large database. Overall, it provides specifications in the codes of practice, and modeling of bond of lap splices in RC structures and hence the development or bond length.

1 INTRODUCTION

When length of reinforcing bars is insufficient to accommodate over full length of a structural member, transfer of forces is through overlapping of two rebars over an adequate *"lap length or splice length"*, from surrounding concrete to steel bars and vice versa. The codes of practice provide minimum lap length for achieving full yield strength of reinforcement bar. The embedment length over which the yield strength of reinforcing bar fully developed is nothing but the development length. Behavior of lap splices with ribs or surface deformations depends on several parameters. Bond is an important factor that transfers stresses in rebars. The strength of lap splices also depends on whether the spliced bars are in contact or separated. For improved performance, rebars should be spliced or lapped over a minimum distance L' or L_d. However, for tension splices a reduced bond stress, "u" is generally used.

2 STRESS TRANSFER AND FAILURE MECHANISM

Stress transfer from deformed bars to surrounding concrete is mainly through mechanical interlocking of lugs. When a deformed bar is pulled out, bar lugs bear against the surrounding concrete with resultant force normal to the plane of the lug, at an inclination of angle β with the axis of bar. The component of the resultant force parallel to the axis of the bar causes shearing of concrete between the lugs, while the normal force component exerts radial force against the surrounding concrete. Force exerted by lugs onto the surrounding concrete is inclined at an angle "β" to the axis of the bar as shown in Fig. 1, which can be resolved in to two components: one along radial direction causing splitting of surrounding concrete cover at ultimate stage and another one along longitudinal direction causing shear stress, *u*. Then the radial stress component causing splitting of the surrounding concrete is $u' = u \tan\beta$. This radial force component is similar to an internal pressure against a thick concrete cylindrical wall. The splitting of concrete occurs when the hoop tensile stress exceeds the tensile strength of concrete.

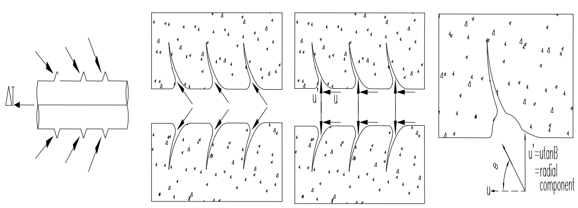

Figure 1. Transfer of forces.

In such occasions, two types of splitting may be possible in lap splices as shown in Fig. 1. Side splitting occurs when the horizontal splitting occurs at the level of bars; whereas the face splitting occurs when the vertical splitting develops in bottom cover below horizontal bars.

3 FAILURE IN LAP SPLICES

The splitting of concrete occurs under high bond stress between steel reinforcement and the surrounding concrete, which is caused by wedging action of lugs against the surrounding concrete that produces hoop tension and leads to failure on the weakest plane along the spliced bars. The strength of splices with lateral ties compared with those without ties, and those with spirals seem to be about 10 percent greater. The spirals placed centrally over the spliced region exhibited slightly higher strength than those with that of the eccentric bars. The stress distribution in spliced bars at the ultimate load exhibits a rapid increase near cutoff ends, which is a very vulnerable location at the maximum stress. The transverse reinforcement surrounding lap splices, either in the form of stirrups or spirals, can improve their behavior and strength, which delays the splitting of concrete. Due to spirals, the bond stress distribution is uniform over the spliced region and failure tends to be more ductile.

4 PROVISIONS ON DEVELOPMENT LENGTH

ACI code [1] provisions for development length stipulate 69 MPa as the upper limit of concrete compressive strength. The reason for such an upper limit is due to the fact that the test data on high strength concrete (HSC) is not significantly available. The development length at a critical section can be estimated by eq. (1),

$$l_d = \frac{9}{10} \frac{f_y}{\sqrt{f_c'}} \frac{\psi_t \psi_e \psi_s \lambda}{\left(\frac{c_b + K_{tr}}{d_b}\right)} d_b \tag{1}$$

Euro Code 2 [2] specifies a simple expression for estimating the development length of reinforcing bars in concrete in eq. (2).

$$L_d = \frac{f_{yd}\ \varphi}{4\ f_{bu}} \tag{2}$$

Indian code of practice [3] provides the development length as a function of yield strength of reinforcement, diameter of bar and the design bond strength, which is a function of the strength of concrete in eq. (3)

$$L_d = \frac{\phi \sigma_s}{4 \tau_{bd}} \tag{3}$$

The development length requirements specified by the codes of practice indicate that the bond strength of concrete is a parameter. Further, the provisions by the codes of practice are limited to normal strength concrete (NSC).

5 REVIEW OF LITERATURE

Prediction of ultimate strength of lapped rebar by varying surface characteristics of rebars has been reported [4]. Change in rib face angle between 48.5° and 57.8° did not affect the bond [5]. Internal cracks at 60^0 inclination with axis of the bar were formed due to local crushing in front of rebar ribs inducing tensile stresses at the tip [6]. Significant experimental and analytical evidence on anchorage bond strength of ribbed bars under monotonic and cyclic loading has been reported [7]. Splitting of concrete is due to lack of lateral reinforcement [5].

Chamberlin [8] emphasized the effect of splice length-to-bar diameter ratio, l_s/d_b, varying between 12 and 21, in which compressive strength of concrete was varied between 30.8MPa and 40.5MPa. As the strength of concrete and cover ratio (C_{so}/C_b) increase, bond strength has been found to be increased. Further, the bond strength increases as splice length-to-diameter ratio, (l_s/d_b) decreases. *Chamberlin* [9] studied the effect of side-to-bottom cover ratio, (C_{so}/C_b). It has been observed that the minimum cover ratio of (C_{so}/C_b) is 2.0 for achieving better splice strength. When the cover ratio (C_{so}/C_b) was greater than 2.0, the splice strength was tended to increase. The splice strength was found to increase by 30% when adequate bottom cover was provided. This is due to the fact that with decrease in the thickness of bottom cover, the lap splice tended to fail in face splitting of bottom concrete. When bars are closely located, splice strength was not affected.

Chinn, Ferguson, and Thompson [10] investigated behavior and strength of lap splices in RC beams. Most beams were provided with a single splice with bars in contact, however, a few of them were provided with two splices symmetrically. The beams were tested with splices in constant moment region. A wide range of variables was observed to affect splice failure. Splitting failures in concrete were classified in to two; bottom, and side splitting. The effect of splitting on bond strength was emphasized further. Analysis of data by *Chinn et al.* [10] reveals that as the ratio of splice length-to-bar diameter increases, bond strength of lap splices decreases. This was observed when maintaining all other parameters more or less constant. As the ratio of side cover-to-bottom cover (C_{so}/C_b) decreases, bond strength decreases for a given (C_b/d_b) ratio. When side cover-to-bottom cover ratio (C_{so}/C_b) is greater than 2.0, only then better bond strength could be achieved keeping other parameters constant. As the strength of concrete increases, the bond strength also increases. It has been further noticed that as the ratio of bottom clear cover-to-bar diameter (C_b/d_b) increases, splice strength also increases.

Ferguson and Thompson [11,12] reported requirements for developing full tensile capacity of bars in RC beams. Tests were performed in beams with cantilever overhanging, which permitted unspliced test bar in negative moment region. It was observed that the anchorage length would have a portion with transverse flexural cracks and the remaining is introduced to determine the strain distributions along the anchor bars. The detailed sequence of the development of failure indicates that many possibilities and variables affect the complicated behavior of splices.

Ferguson and Breen [13] investigated on lap splices of high strength reinforcing bars. Splice length requirements in constant moment region to develop defined tensile stress in larger diameter steel bars have been proposed. Flexural cracking was followed by splitting of concrete along the splice, which was initiated near the end of the spliced bar and increased with further loading until just before the failure. In addition, secondary diagonal tension cracks were also formed in some cases. *Ferguson and Breen* [13] studied the effect of splice length-to-diameter (l_s/d_b) ratio, (C_b/d_b) ratio, strength of concrete and transverse reinforcement on splice strength. Diameter of spliced bars was varied from 25.4 mm to 35.8 mm. The ratio of (l_s/d_b) was varied from 18.0 to 59.0, with bottom cover-to-diameter ratio, (C_b/d_b) ranging from 0.90 to 1.8, and side cover-to-diameter (C_{so}/C_b) ratio greater than 2.0. The compressive strength of concrete was varied from 13.2 MPa to 38.7 MPa. The bond strength decreases as (l_s/d_b) ratio increases. Also as the bottom cover-to-diameter ratio (C_b/d_b) increases, the splice strength increases. With addition of transverse reinforcement, the splice strength was found to increase. With the combination of larger splice length-to-diameter ratio (l_s/d_b) and smaller bottom cover-to-diameter ratio (C_b/d_b), splice strength was found to be reduced significantly. It reveals that the conventional design criterion of providing nominal cover could lead to premature splitting failures, and hence improper strength development of splices in RC members. The ratio of bottom cover-to-bar diameter (C_b/d_b) is a predominant design parameter.

Ferry and Thompson [14] reported studies on bond stress distribution in reinforcing steel bars in beams and pullout specimens. The bond stress and its distribution on a given specimen at different loads were different and a shift in the point of maximum bond stress for different concrete strengths was observed. The results with eccentric pullout specimens and the stress distribution adjacent to a crack in a beam were observed to be similar. The maximum ultimate stresses for each were the same.

Fergusan and Krishnamurthy [15] tested 32 spliced beams using 11 mm diameter bars to understand the transition from face split to face and side split, strength of V-type failure, and possible avoidance in a wall of weaker face and side split mode. The beams contained six bar splices centered along the width, modeled as widely spaced splices. The main reinforcement was 0.62% in beams of 300 mm width using 11 mm diameter bars. The splice length and cover to the bar were varied in nonuniform moment region. The effect of the bar diameter on splices was studied under constant moment confined with transverse stirrups and spirals. The splice length was varied from 24 to 26.7 times the bar diameter. The presence of stirrups added to splice stress, and the stress improvement in large size bars is substantial. The transverse reinforcement improved the strength

(1) by picking up tension where concrete was splitted, with a capacity far beyond that of the concrete it replaces and
(2) slowing down further spread of splitting and thus helping the concrete indirectly.

Zekany et al. [16] studied the effect on strength of splices. The level of shear stress, quantity and configuration of transverse reinforcement, casting position of splice, concrete strength, concrete consistency, bar size, and splice location along shear span on the strength of splices were studied under shear predominant loading. The beams were over hung over simple supports. The splices were arranged at top and bottom faces of the beams so as to use them after another as bottom cast and top cast bars. The level of shear force showed an inconsequential influence on strength of lapped splices. Substantial increase in the level of shear force caused negligible impact on splice strength. The increase in transverse reinforcement improved the bond strength as well as the shear strength of section. The splice strength is controlled by the lap length and cover or spacing. The transverse reinforcement with more intermediate legs is effective in improving the bond strength of splice. The average bond strength ratio of top bar-to-bottom bar was 0.90. The top bars performed well with low slump concretes, one end of splice started cracking at the section of the maximum moment. In all the cases, flexural crack appeared at one end of the splice over the support and shear cracks were developed after formation of flexural cracks along the splice. It was noticed that the location of splice in shear span influenced the behavior of splice.

Thomson et al. [17] studied the effect of ratio of (l_s/d_b), (C_b/d_b), and strength of concrete on splice strength. The splice strength was improved when (C_b/d_b) ratio is greater than 2.0 with lateral reinforcement showing significant improvement of splice strength. At low ratios of (C_b/d_b), splice strength has been found to be reduced very significantly. It has been further noticed that at (l_s/d_b) ratio of 36.0, splice strength was found to increase when (C_b/d_b) ratio increased [12]. *Mathey and Watstein* [18] reported that as the splice length ratio, (l_s/d_b) was doubled from 14.0 to 28.0, the splice strength was reduced by more than 40 percent. Further, as (C_b/d_b) ratio was increased from 1.5 to 3.5, splice strength was increased to more than 135 percent. In other words, when (C_b/d_b) ratio is reduced from 3.5 to 1.5, at (l_s/d_b) ratio of 14.0, splice strength was found to reduce to about 55 percent. Other parameters such as (C_{so}/C_b) are 2.0 and the strength of concrete was varied between 25.0-30.0 MPa at constant transverse reinforcement. The splice strength at small (l_s/d_b) ratios, when (C_b/d_b) ratio was decreased from 3.5 to 1.5 was found to be even significantly high.

Hester et al. [19] studied on splice strength at (C_b/d_b) = 2.0, (C_{so}/C_b) = 1.0, and (C_{si}/C_b) = 1.5 with compressive strength of concrete varying between 36.1 MPa and 44.5 MPa. There has been hardly any improvement of splice strength even when transverse reinforcement was provided. However, there exists an improvement of splice strength by providing transverse reinforcement. As (l_s/d_b) ratio increased, there is a slight decrease of splice strength. This shows that (C_b/d_b) ≈ 2.0 seems to be a reasonable limit to obtain sufficient confinement without transverse reinforcement. When a minimum value of (C_b/d_b) ≈ 2.0 is maintained, results showed that the effect of transverse reinforcement was not very significant to improve the splice strength. For given conditions, splice strength seems to be a constant. It does not vary by altering other parameters provided that the minimum bottom cover-to-diameter (C_b/d_b) ratio is maintained for given splice length-to-diameter (l_s/d_b) ratio. Hester et al. [20] reported some experimental investigations on 36 beam splices by changing casting position, bar size and anti-bleeding agent in concrete. Steel reinforcement had bamboo i.e. parallel deformation pattern with epoxy coating thickness equal to 0.2mm. Coated bars showed strength about 84 percent of that of bond strength of uncoated bars. *Choi et al.* [21] studied the effect of bar diameter on the splice strength with transverse reinforcement. The ratio of bottom cover-to-diameter ratio (C_b/d_b) was varied between 1.3 and 1.6, and splice length-to-diameter ratio (l_s/d_b) was varied between 16.0 and 19.0. The compressive strength was varied between 37.0 MPa and 41.4 MPa. The splice strength was found to be observed between 3.8 MPa and 5.7 MPa. At bottom cover-to-diameter ratio (C_b/d_b) = 16.0, splice strength was reduced from 5.2 MPa to 4.6 MPa when transverse reinforcement was reduced by 50 % or when spacing of bars was increased from 284 mm to 510 mm, splice strength was reduced by 10%. When ratio of C_s/d_b is very small or less than 2.0, the effect of transverse reinforcement seems to be very significant. This shows that with a very minimum influence of other parameters or when other parameters are kept constant, splice strength was found to decrease by 30 percent as bar diameter increased from 15.9 to 35.8 mm. Choi et al. [22] reported results of 15 beams tested in negative bending with multiple splices in the middle without stirrups in splice region. The parameters in this study are bar diameter (16, 25 and 36mm) and bar deformation pattern. Ratio of bond strength of splices ranged from 0.54 to 0.94 with an average value of 0.83.

Hamad and Jirsa [23] tested 12 beams with multiple splices at the center of the beam in negative bending moment region with coating thickness of 0.2mm at the bar surface. Bond strength of epoxy coated bar splices with 36mm diameter bars was increased from 74 percent without transverse reinforcement to 80 to 85 percent with transverse reinforcement. The increase was independent of number of splices or bar spacing. Increase in bond strength was varied from 67% to 74% with 20mm diameter bars. *Abrishami et al.* [24] reported that up to yielding of reinforcement epoxy coating does not change the overall load-deflection response of concrete beams. The epoxy coating resulted in fewer wider cracks, and more splitting cracks. *Idun and Darwin* [25] found that epoxy coating is less detrimental to bond strength with reinforcement bars with high relative rib area. It was also found that epoxy coating on bar surface causes less reduction in the bond strength when the rib face angle is greater than 43 degrees. *Cairns and Abdullah* [26] investigated on bond strength of epoxy coated 16mm diameter bars with relative rib area of 0.064, rib inclination of 57 and 90 degrees, rib face angle varying between 30 to 75 degrees, rib spacing of 10.8 mm for factory made bars and 12 mm for machined bars. The coating thickness was ranged from 0.21 to 0.24mm. The friction between concrete and epoxy coating as compared with mill scale steel surface was reduced by 40 percent at low stress levels. *Hester et al.* [20] tested 65 beam and slab specimens. It has been observed that epoxy coating significantly reduced the splice strength. The decrease in splice strength is independent of degree of transverse reinforcement.

As reported, work of *Treece and Jirsa* [28] is the basis for development length modification factors for epoxy coated bars in specifications. In ACI 318, development length is multiplied by a factor 1.5 for epoxy coated bars with cover less than 3 times bar diameter or the clear spacing between the bars less than 6 times bar diameter and a factor of 1.2 for other cases, with a maximum factor of 1.7 for the product of top bar factor and epoxy coating factors. In AASHTO bridge specifications the above three factors are 1.5, 1.15 and 1.7 respectively. Two of the most commonly used modeling approaches have been provided by [29,30] using nonlinear regression analysis of test data.

6 DEVELOPMENT OF ANALYTICAL EXPRESSIONS

To start with, various factors influencing the splice strength in RC beams have been identified. The influence of each one of these factors on the splice strength in RC beams has been evaluated. A total of 895 data points have been segregated and analysed for developing the expression for the splice strength [31]. The efficiency of the developed equations has been compared with reference to various parameters influencing the bond strength.

6.1 Influence of Compressive Strength of Concrete

For all practical purposes, the compressive strength of concrete is recognized as the most important factor for assessing the quality of concrete. When the test data is limited, the modulus of rupture and the split tensile strengths can be estimated as $f_t \ or \ f_r = k\sqrt{f_c^{'}}$, where f_t = split tensile strength, f_r = modulus of rupture, $f_c^{'}$ = cylinder compressive strength of concrete and k = constant, that can be obtained from the test data. Further, most of the codes have formulated square root of the compressive strength, $\sqrt{f_c^{'}}$ for estimating the bond strength of concrete. A simplified expression by ACI 318 [1] (2008) for predicting the splice strength in RC beams is based on the tests on RC beams made of normal strength concrete (NSC). However, the splice strength in RC beams made of high strength concrete (HSC) tends to deviate from the square root of the compressive strength of concrete.

The effect of the compressive strength of concrete on splice strength shows that the rate of increase of splice strength is not proportional to the rate of increase in compressive strength of concrete for various levels of confinement by lateral reinforcement.

From the observations, a power law in the form of $y = ax^b$ seems to fit well with the experimental data. The splice strength is better correlated with the cubic root of compressive strength ($\sqrt[3]{f_c^{'}}$) or with 0.3 power on compressive strength rather than square root ($\sqrt{f_c^{'}}$) when majority of the data consist of results on high strength concrete (HSC) beams. Similar consensus has been observed from other studies. When the number of data points is increased and also the data points with high strength concrete increased, the splice strength seems to be predicted well with the fourth root of the compressive strength.

6.2 Influence of Diameter of Spliced Bar

Up to a diameter of about 20mm, the splice strength seems to be not influenced with the bar diameter. When the bar diameter increases beyond 20mm, there seems to be a significant influence of the bar diameter on the splice strength. The splice strength has been observed to vary with the bar diameter with a power of 0.2. The trend of variation of splice strength normalized with the fourth root of compressive strength of concrete verses the spliced bar diameter shows that as the bar diameter increases the splice strength in RC beams increases.

6.3 Influence of Embedment Depth-to-Diameter Ratio

The embedment depth-to-diameter ratio has significant influence on the splice strength. The splice strength varies as square root of embedment depth-to-diameter ratio. However, the analysis of the large experimental data on splice strength shows that the splice strength varies as a function of the embedment depth-to-diameter ratio with a power of 0.55.

6.4 Influence of Bar Rib Geometry

The influence of the rib geometry is related with the rib index or reinforcement index, which is related to the bar rib height and the spacing of the ribs. The studies reported different rib geometry and different rib pattern. When considering all the parameters in to account, the splice strength varies as a power of 0.02 with the bar rib ratio. The increase in the contribution of the rib geometry through mechanical bond dowel action has been observed to be significant with proper lateral confinement. As the quantity of the lateral reinforcement or the level of the lateral confinement increases, the contribution of the rib geometry seems to be improved.

6.5 Influence of Concrete Cover-to-Reinforcement

Depending up on the thickness of the cover, lap splice can fail either due to splitting of cover with small thickness or pull out of reinforcing bars at large cover-to-reinforcement bars. From the large selected experimental data base available with various combinations of concrete cover and the quantity of lateral reinforcement, the splice strength expression has been developed in terms of concrete cover and transverse reinforcement index. In the final form for splice strength, minimum thickness-to-diameter ratio and ratio of maximum thickness-to-minimum thickness are also appropriately incorporated.

6.6 Influence of Transverse Reinforcement

The lateral reinforcement in the form of stirrups influences the splice strength due to confinement effect. The confinement of lap splices depends up on lap length, diameter of lap splice bar, diameter of stirrup legs, spacing of stirrups and yield strength of reinforcement bars. In this study, combining the above parameters, transverse reinforcement index has been derived based on the mechanics of lap splice in direct tension. The combined effect of concrete cover and quantity of lateral reinforcement can be defined through another index called transverse index. The splice strength varies as a function of the cube root of transverse reinforcement index.

7 PREDICTIVE EQUATIONS FOR SPLICE STRENGTH

The research findings indicate that the behavior and failure mechanism of lap splices in tension in RC members are influenced by various parameters. To develop a general expression to estimate the splice strength considering the failure mechanism into account is very complex and not simple to conclude. Under such circumstances, empirical equations developed based on nonlinear regression analysis (NLRA) are useful for predicting the splice strength incorporating all influencing factors. The factors influencing the splice strength in RC beams are i) compressive strength of concrete, $f_c^{'}$, ii) bar diameter, d_b, iii). embedment depth-to-diameter (l_s/d_b) ratio, iv) rib geometry, R_{rr} v). concrete cover- to-reinforcement, C, and vi) lateral reinforcement, C_r. In this, different formulations have been attempted and the initial exponents c_1, c_2,....c_n, corresponding to the mentioned influencing parameters are assigned certain values based on evaluation of the influence of each parameter, and range obtained from NLRA.

8 DEVELOPMENT OF EXPRESSIONS

Various forms were attempted for estimating the splice strength in RC beams. The final form to be developed should be based on the influence of individual parameters, with due modifications for the indices and coefficients in the multiple regression analysis. The proposed form for estimating the stress in steel reinforcement at the lap splice in RC beams incorporating the parameters is the following form

$$\sigma_s = P[f_{cm}]^{c_1}\left[\frac{l_s}{d_b}\right]^{c_2}\left[\frac{20}{d_b}\right]^{c_3}[R_{rr}]^{c_4}\left[\left(\frac{C_{min}}{d_b}\right)\left(\frac{C_{max}}{C_{min}}\right)^{c_5}+9.5K_{tr}\right]^{c_6} \quad (4)$$

The strength or bond strength of lap splice can be estimated from the relationship between the strength of steel bar and the bond strength

$$\sigma_b = Q[f_{cm}]^{c_1}\left[\frac{l_s}{d_b}\right]^{c_7}\left[\frac{20}{d_b}\right]^{c_3}[R_{rr}]^{c_4}\left[\left(\frac{C_{min}}{d_b}\right)\left(\frac{C_{max}}{C_{min}}\right)^{c_5}+9.5K_{tr}\right]^{c_6} \quad (5)$$

The constants P and Q, and exponents' c_1, c_2, c_3, c_4, c_5, c_6, and c_7 have been adjusted through NLRA. After refining the coefficients in the regression analysis, the final form for steel strength and splice strength are as follows

$$\sigma_s = 33[f_{cm}]^{0.25}\left[\frac{l_s}{d_b}\right]^{0.45}\left[\frac{20}{d_b}\right]^{0.20}[R_{rr}]^{0.02}\left[\left(\frac{C_{min}}{d_b}\right)\left(\frac{C_{max}}{C_{min}}\right)^{0.33}+9.5K_{tr}\right]^{0.33} \quad (6)$$

$$\sigma_b = 8.25[f_{cm}]^{0.25}\left[\frac{l_s}{d_b}\right]^{-0.55}\left[\frac{20}{d_b}\right]^{0.20}[R_{rr}]^{0.02}\left[\left(\frac{C_{min}}{d_b}\right)\left(\frac{C_{max}}{C_{min}}\right)^{0.33}+9.5K_{tr}\right]^{0.33} \quad (7)$$

Where,
n_l = Number of splices enclosed by one stirrup
n_{t1}= Number of legs over the cross-section
n_{t2}= Number of transverse legs over the lap length
a_{st}= Area of cross section of one leg of the transverse (bar) steel.
d_s = Diameter of the spliced bar
l_b = Bond (splice) length
$n_{t_1} a_{st}$ = Area of all legs enclosed = $A_{st} = n_{t_1} a_{st}$
a_{st} =Area of one leg of transverse steel.
a_{sl} = Area of one spliced (enclosed) rebar
S_t =Spacing of stirrups
a_{st} = Area of one leg of transverse bar
n_t = Number of legs enclosing the splices
a_{sl} = Area of one spliced bar
n_l = Number of spliced (enclosed) bars
d_s = Diameter of spliced (enclosed) bars
s_t = Spacing of transverse bars
η = Effectiveness factor
= 1.0 stirrups or spirals
= 0.3 straight bars
= 0.0 straight bars

$$K_{tr} = \left[\frac{n_t a_{st} d_s}{n_l a_{st} s_t}\right]\eta$$

n_t = No of links/stirrups crossed splice length
n_l = No of bars spliced
d_s =Diameter of spliced bars
s_t = Spacing of stirrups
a_{st} = Area of cross section of one leg of stirrups
a_{sl} = Area of cross-section of one spliced bar
η = Effectiveness factor

The value of transverse reinforcement contribution is restricted to

$$\left[K_{tr} = \frac{n_t A_{st} d_s}{n_s A_s s_t} \right] \leq 0.3$$

$\frac{c_{\min}}{d_b} \geq 1.0$ [i.e. minimum cover should be equal to the diameter of the spliced bar]

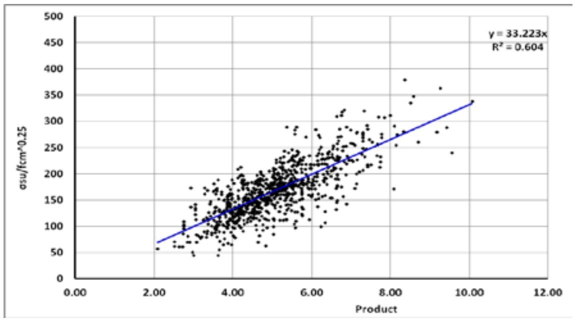

Figure 2. Applied steel stress vs. Product of parameters.

Fig. 2 shows the variation of experimental stress observed in the spliced steel bar with the stress in steel calculated using the proposed expression in the present study. The deviation of the trend line with reference to the experimental and the calculated steel stress is symmetrical with reference to both the axes.

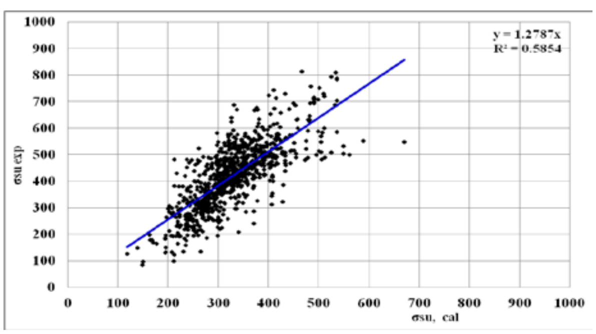

Figure 3. Applied steel stress vs. Calculated steel stress.

Among the various trends attempted, the strength of the steel normalized with the fourth root of compressive strength seems to be better estimated. The trend line exhibited the lowest deviation of the individual results from the mean. The coefficient of variation is the lowest with this trend. Fig. 3 shows the variation of splice strength ratio with the compressive strength of concrete. Overall the prediction of the splice strength is better by using fourth root of concrete compressive strength. As the compressive strength of concrete increases majority of the data points are lying above the horizontal line showing that the prediction is better for higher grade concrete with the fourth root of compressive strength instead of the square root.

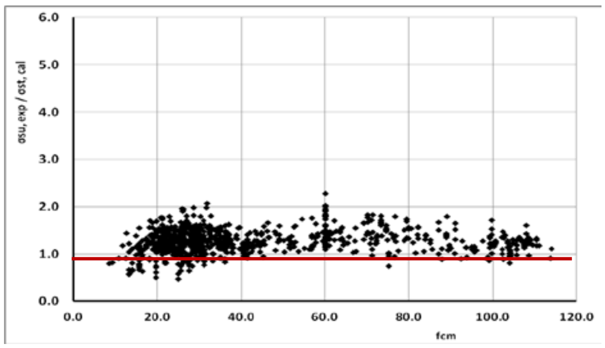

Figure 3. Splice Strength vs. Compressive strength of concrete.

As shown in Fig. 4, the variation of splice strength ratio with the embedment depth-to-diameter ratio, the majority of the data points with the present form of splice strength lie above the horizontal line corresponding to the splice strength ratio of 1.0. The prediction looks reasonably good.

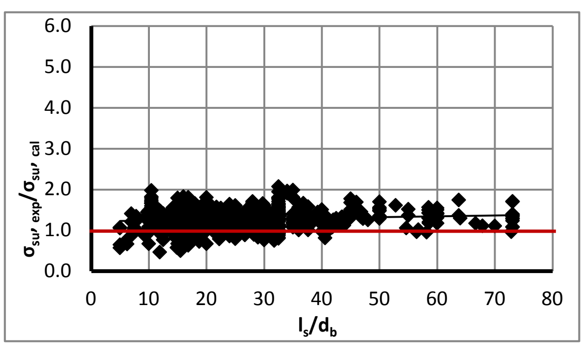

Figure 4. Strength vs. embedment depth-to-diameter ratio.

As shown in Fig. 5, when the diamater of the reinforcing bar increases up to 20mm, there has been a nonnegligible change in the splice strength with increasing the diameter. As the bar diameter increases beyond 20mm, there has been a decrease in the splice strength with the bar diameter. The effect of the bar diameter predcits well the splice strength with $(20/d_b)^{0.2}$ form in the splice strength expression. In the present form, the effect of spliced bar diameter, in which the splice strength decreases with increase in the spliced bar diameter has been incorprated reasonably.

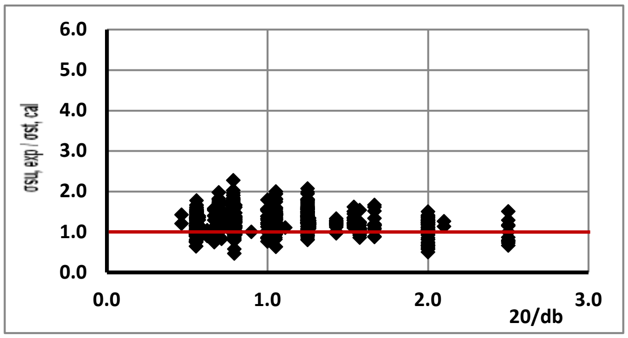

Figure 5. Strength ratio vs. Bar diameter.

Fig. 6 shows the effect of the relative rib area on the splice strength. The relative rib area influences the splice strength, with 0.02 power. Figs. 7 and 8 show the influence of concrete cover-to-reinforcement bar on the splice strength. The splice strength is influenced by the minimum concrete cover-to-the bar diameter and also the ratio of maximum cover-to-the minimum cover.

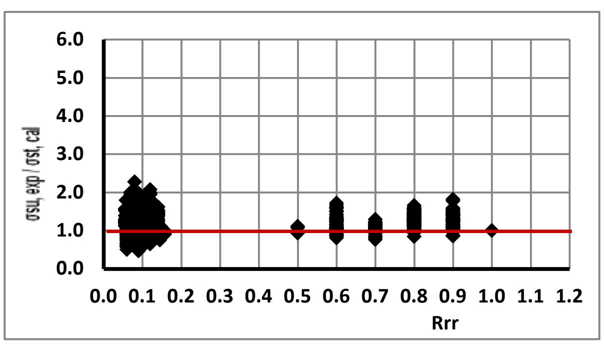

Figure 6. Strength ratio vs. Relative Rib Area.

Appropriately, these parameters are selected to represent in the final splice strength expression. As the cover to the reinforcement increases, there has been a better confinement from the surrounding concrete to the reinforcement, which will constrain the splitting of concrete.

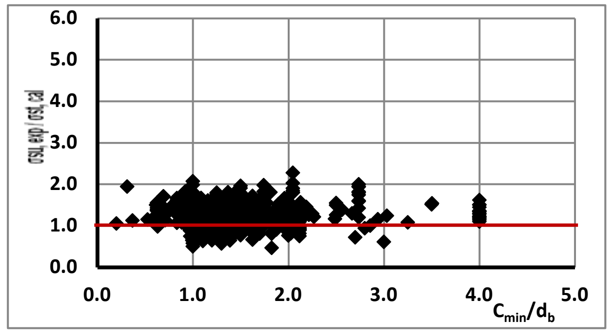

Figure 7. Strength vs. Cover-to-diameter ratio.

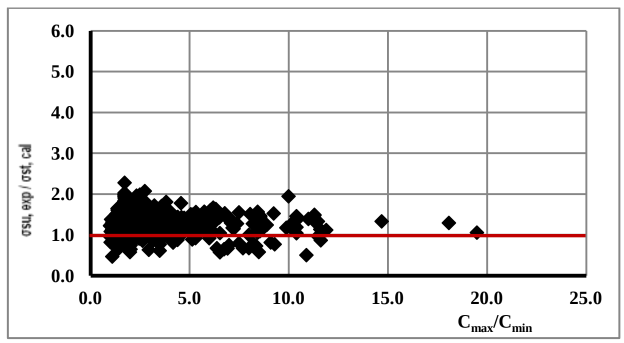

Figure 8. Strength vs. Concrete cover ratio.

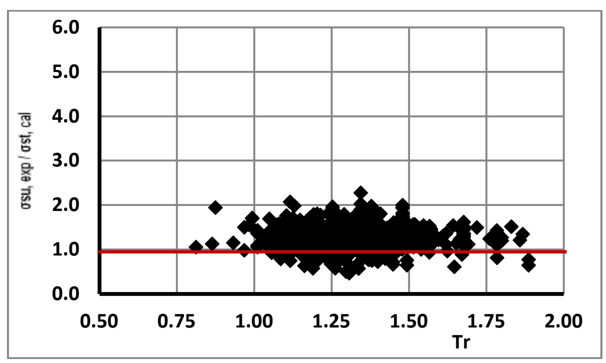

Figure 9. Strength ratio vs. Confinement index.

The transverse reinforcement provided to the spliced bars can also help in controlling the splitting cracking in the beams. The total confinement achieved through concrete cover and the transverse reinforcement is considered through total transverse confinement index T_r. Fig. 9 shows the variation of splice strength with transverse reinforcement index. The representation of this confinement index on the splice strength in reinforced concrete has been observed to be reasonably good.

9 CONCLUSION

A nonliner regression analysis of large experimental data has been carriedout for undertsanding the influence of parameters on lap splices in reinforced cncrete. The proposed equation predicts reasonably well with the influence of individual parameters incorporated on splice strength. The size of bar has been correctly incorporated along with other influencing factors.

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