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A Review of Australian Design and Construction Practices Concerning Anchorage and Lap Splicing of Reinforcing Bars, with Particular Emphasis on Slabs and Walls

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1. Introduction

The origin and in-depth use of the long-standing, simple and effective design rules in Section 13 of AS 3600, for calculating the tensile development and lap lengths of straight, deformed reinforcing bars are explained. Some useful improvements to the current rules are recommended.

A fundamentally important concept on which the design rules in AS 3600 are based is that tensile development length and tensile lap length are synonymous. This is shown to be because bars being anchored or spliced near a free surface exhibit the same types of failure modes involving longitudinal splitting of the concrete. Practice should continue to benefit from this.

2. Tensile lap splices in slabs and walls

Experienced steel reinforcement industry sources have estimated that over 60% of all Class N reinforcing bars used in building construction in Australia are either 12 or 16 mm in diameter, and a large proportion of these small diameter bars find their way into slabs and walls as main reinforcement, where they are often lapped. Importantly, this major segment of the Australian steel reinforcement market is estimated to represent over 80% of all reinforcing steel produced by length. Assuming that lapped splices occur over 5% of the total length of these bars, then (say) doubling the length of lapped splices in slabs and walls could result in 4% more bar having to be produced by length. This could indeed occur if alternative design rules developed by Gilbert (2007b) were adopted. In monetary terms, this would cost the construction industry and broader community tens of millions of dollars each year in extra material alone. Due to the sheer magnitude of this part of the steel reinforcement market, it will form the main focus herein.

3. Calculation of tensile lap length in accordance with AS 3600 and useful improvements

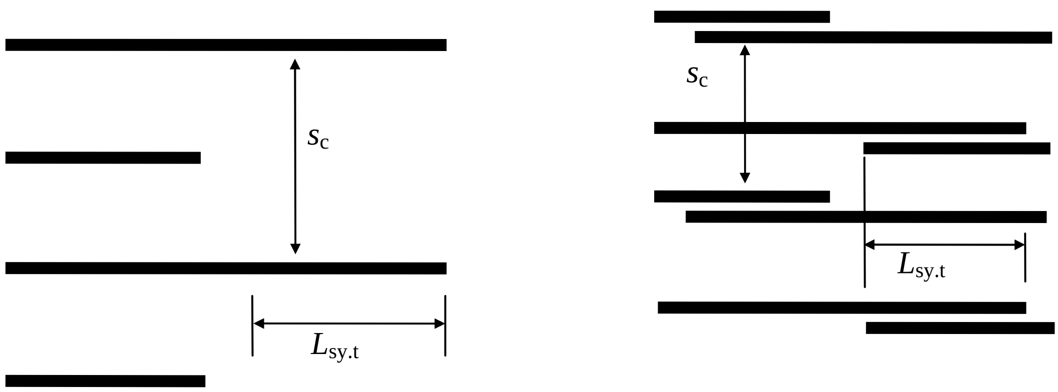
3.1 Tensile lap length equals tensile development length, $L_{sy.t}$

In accordance with Clause 13.2.2 *Lapped splices for bars in tension* of AS 3600–2001, "*The lap length for splices for bars in tension shall be not less than the development length ($L_{sy.t}$) given in Clause 13.1.2.1.*" The wording of this clause has remained unchanged since the rules for calculating tensile development and lap lengths in AS 3600–2001 were first introduced into AS 3600–1988, except for the clause referencing. This clause can most simply be interpreted to mean that the tensile lap length equals the tensile development length $L_{sy.t}$, as given by Eq. 1, and the benefits to be gained by adopting this simple approach are described in Section 3.2:

$$L_{sy.t} = \frac{k_1 k_2 f_{sy} A_b}{(2a + d_b)\sqrt{f'_c}} \geq 29 k_1 d_b \quad \text{(note: term on RHS of inequality is } 25k_1d_b \text{ in AS 3600–2001)} \qquad (1)$$

where f'_c equals the characteristic compressive cylinder strength and may not exceed 65 MPa; coefficient k_1 equals 1.25 for horizontal bars with more than 300 mm of concrete cast below the bars, or 1.0 for all other bars; coefficient k_2 equals 1.7 for bars in slabs and walls if the clear distance between adjacent parallel bars developing stress is not less than 150 mm, or 2.2 for longitudinal bars in beams and columns with fitments, or 2.4 for any other longitudinal bar; and variable* a *equals the smaller of the (least) concrete cover to the deformed bar or half the clear distance to the next parallel bar developing stress,* s_c*, and currently has no upper or lower limits.

Warner et al. (1989) provided elementary commentary material about the stress development rules when they were first published in AS 3600–1988, stating that "*A re-evaluation of test data has shown that the splice length is equal to the development length $L_{sy.t}$…and no additional multiplying factors are needed as required by the previous code.*" Ferguson (1989) shed further light on how to interpret Clause 13.2.2 of AS 3600–1988, according to the CIA at the time, by presenting the two figures shown in Fig. 1. They show the effect of staggering bar anchorage (Fig. 1(a)) or bar splicing (Fig. 1(b)). It is apparent from Fig. 1(b) that the clear distance between bars developing stress is affected by the width of the spliced bars, assumed to be lapped in the same plane and also in contact with each other. It follows from Fig. 1(b) that in the case of in-plane contact splices, the clear distance, s_c, equals the centre-to-centre spacing of bars developing stress, s, less two times the bar diameter, d_b (when splicing bars of equal diameter).



(a) Anchorage (b) Splicing

Figure 1 Definition of clear distance, s_c, between staggered bars (Ferguson 1989)

Both of the diagrams in Fig. 1 have been reproduced in the latest 2007 edition of the CIA Reinforcement Detailing Handbook (CIA 2007), confirming that the CIA has not changed its definition of clear distance, s_c, in particular when contact lap splices are used.

In his commentary to AS 3600–1988, Walsh (1988) similarly explains that "*An important new feature of Section 13 is that the development and the splice lengths are the same.*" However, confirming the CIA approach described by Ferguson, he goes on to say that "*In design some care is needed in applying this concept. ….. As to the bar spacing effect, the appropriate maximum value of a is half the clear distance to the next bar in a splice. If adjacent bars are being spliced the distance a is half the clear distance between adjacent parallel bars or the cover as stated in the Standard. This distance must take into account the extra space occupied by the bars being spliced.*" This more detailed explanation is clear from Fig. 1(b).

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Two tables of deemed-to-comply tensile development lengths (Tables 13.1.2.2(A) and (B)) were included in AS 3600–1988, which were directly referred to from the clause entitled *Lapped splices for bars in tension* (Clause 13.2.3 at the time). Users of the Standard could select development or splice lengths directly from these tables, without having to perform any calculations, provided the conditions of the deemed-to-comply clause (13.1.2.2) were satisfied.

In particular, in Clause 13.1.2.2 it was necessary that: (i) for slabs and walls, the clear distance between adjacent parallel bars developing stress was not less than 150 mm; and (ii) for beams and columns, fitments were provided and the clear distance between bars was not less than twice the cover. More specifically, for slabs and walls, the clear distance, s_c, can affect the value of k_2, and for beams and columns with fitments, the same value of tensile development or splice length, $L_{sy.t}$ would be calculated if $2a$ equalled twice the minimum cover to any concrete surface.

It follows that in accordance with AS 3600–1988, the tensile splice length could be taken as equal to the tensile development length provided that specific conditions were met. Therefore, this assumption was not always valid, and its generality appears to have been overstated by some, e.g. Warner et al. (1989). Nevertheless, in many practical cases, as shown by the two tables in AS 3600–1988, and more extensive tables generated by Ferguson (1989) which were referred to in the commentary to AS 3600–1988 (1990), this is a valid assumption, and accordingly has commonly been applied in practice.

A general requirement applied in AS 3600–1988 (Clause 13.2.1(b)) to lapped splices was that lapped portions of bars had to be in contact "*unless shown otherwise on the drawings*". There was absolutely no requirement in AS 3600–1988, in such cases of contact splices, that the clear distance between adjacent parallel bars developing stress, s_c, had to be assumed to equal zero, which would result in $a = 0$ when calculating $L_{sy.t}$ using Eq. 1. Nor was there any requirement whatsoever in the case of contact lap splices that the value of clear distance, s_c, like shown in Fig. 2(b), had to be halved when calculating $L_{sy.t}$ using Eq. 1, which Gilbert (2007a) assumed based on his own perceptions about bar bond when calculating lap lengths using Eq. 1.

The normal requirement for lapped bars to be in contact with each other remained in force in AS 3600–1994, with the rules in Section 13 of AS 3600–1988 staying unchanged. In current AS 3600–2001, Clause 13.2.1(b), which had been in AS 3600–1988 and AS 3600–1994, was dropped, and no mention was made about the lapped portions being in contact. An extensive amount of technical literature supports the approach of not normally having to differentiate between contact and non-contact splices in design, e.g. ACI (2003).

3.2 Benefits of using tensile development length ($L_{sy.t}$) as tensile lap length

Over the course of time, very significant benefits have been realised by the Australian concrete construction industry, by using tensile development length, $L_{sy.t}$, as the tensile lap length (when appropriate, as described above), some of which are not immediately apparent. In particular:

- it has been unnecessary to specifically calculate lap as distinct from development lengths;
- the values of standard development lengths calculated have normally applied to a wide range of practical situations;

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- on site, the same values have applied whether anchoring or lapping straight bars, reducing construction errors;

- staggering of bars, although potentially beneficial, has not normally had to be considered;

- it has been acceptable to splice bars anywhere for full strength, provided the level of congestion has been acceptable, i.e. the clear distances have been sufficient;

- the different values of k_2 provided in AS 3600–2001 have made taking account of the beneficial effects of fitments (ties and stirrups in columns and beams, respectively), straightforward, without having to carefully consider the details of each design, while for slabs it has appropriately been ignored as it is normally only beneficial in one direction;

- during design, lapped bars have been assumed to be in contact with each other when calculating clear distance; and

- on site, it has been understood that bars may or may not be lapped in contact with each other, making placement and inspection much easier, and allowing reinforcing systems, for which making contact splices can be difficult, to be used without complication.

The Australian construction industry has grown to depend on this simple approach being adopted in both the design and scheduling office, and on site, which has also proven to be very economical for all parties involved. Significant economic savings have clearly resulted for consumers of the products and end users of the buildings.

3.3 Useful improvements to AS 3600–2001

Patrick, Turner and Keith (2007) have explained why the following useful improvements should be made to the rules in Section 13 of AS 3600 for calculating tensile development & lap lengths:

- The term $2a$ in Clause 13.1.2.1 should be redefined as twice the cover to the deformed bar or clear distance s_c (see Fig. 1) between adjacent parallel bars developing stress, assuming lapped bars to be in contact, whichever is less, but the value used in the calculation shall not be less than $2d_b$, and nor shall it exceed $6d_b$. Therefore, in Eq. 1, $3d_b \le (2a + d_b) \le 7d_b$.

- The lower bound to $L_{sy.t}$ should be increased to $29k_1d_b$ for D500N bars (as shown in Eq. 1).

- It should be made absolutely clear that lapped bars do not have to be in contact in the field. In this regard, a suitable upper limit can be defined for the centre-to-centre spacing of two bars in a non-contact lap splice: the lesser of one-fifth of the lap length and 150 mm, except for slabs and walls with bars not exceeding 20 mm in diameter it can be 150 mm.

- The upper limit applied to f'_c could be increased to 100 MPa.

4. Derivation of formula for $L_{sy.t}$

4.1 Design approach credited to Orangun et al. (1975)

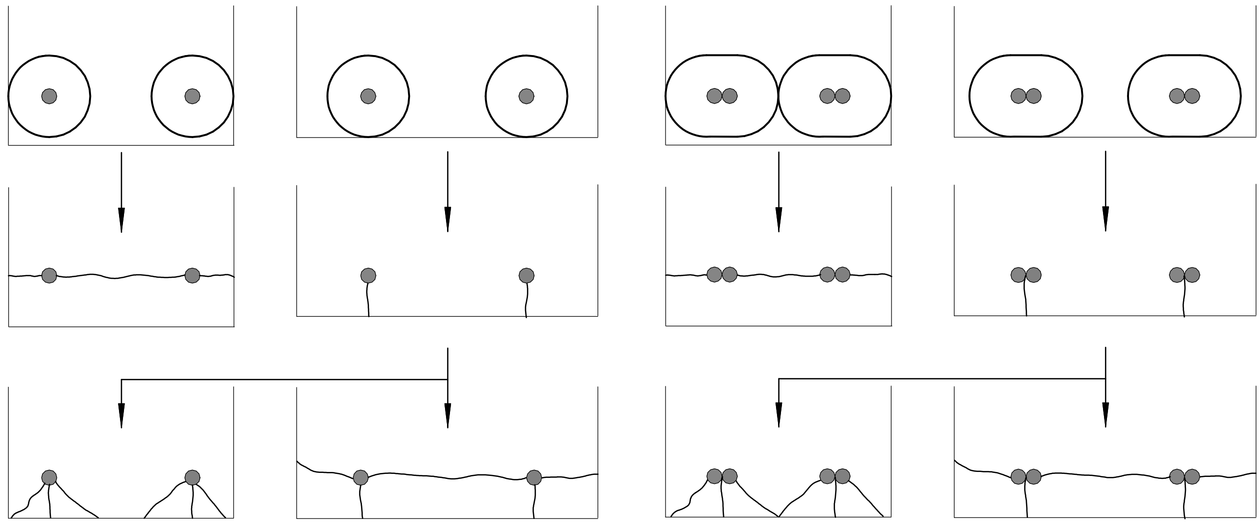
Walsh (1988) explained that when Eq. 1 was derived, the data from no fewer than 286 bar splice tests and 254 bar stress development tests were used as part of the safety calibration process, and makes it clear in his commentary that the term 2*a* would have been calculated in accordance with Fig. 1, i.e. the CIA interpretation. Moreover, Walsh makes it very clear in his commentary material that Eq. 1 was equally accurate at predicting tensile lap lengths as predicting tensile development lengths, when using the CIA interpretation. Walsh also explains the derivation of k_2, and again, for contact lap splices the term 2*a* would have been calculated the same way.

Although the source is not clearly identified, it appears very likely that the 540 test results used by Walsh came directly from a detailed report by Orangun et al. (1975), which is summarised by Orangun et al. (1977). Moreover, it would appear that Orangun et al. (1975, 1977) can be credited with the discovery that test results indicate that development length and splice length can be treated as synonymous in design.

Orangun et al. (1977) clearly stated when describing their bond formula that "*Similar behaviour in cracking and splitting has been observed in tests for development lengths and lap splices (Fig. 2). Therefore, the empirical equation for splice strength should be applicable to development lengths…..There is no definitive trend for splice or development length tests to be segregated. For the same bar diameter, cover, clear distance, and concrete strength, the same length is required for a lap splice as for development length.*"

Figures 2 and 3 from Orangun et al. (1977) are reproduced in Fig. 2 below, which is fundamentally important to this discussion. The CIA interpretation conforms to both of their figures in Figs 2(a) and (b), in particular Fig. 2(b), and even more particularly the top left-hand diagram in Fig. 2(b). From this diagram, it is absolutely clear that the clear distance between adjacent bars developing stress in a contact splice is the actual clear distance.

Moreover, referring to their Fig. 2, they explain that "*Stress from a deformed bar is transferred to the concrete mainly by mechanical locking of the lugs with the surrounding concrete. The resultant force exerted by the lugs on the concrete is inclined…and the radial component causes splitting of the surrounding concrete at failure…In a lap splice where the bars are side by side, the two cylinders to be considered for each splice interact to form, in section, an oval ring, as shown in Fig. 2(b). The failure patterns are similar to those of single bars.*"



(a) Single bars developing stress *(b) Contact lap splices*

Figure 2 Idealised radial stress zones around bars in development lengths or contact splices, and corresponding similar longitudinal splitting modes of failure – Orangun et al. (1975)

Reynolds and Beeby (1982) subsequently investigated the relationship between anchorage and lap lengths, stating that "..*Orangun, Jirsa and Breen, from their extensive study of test data, find that the same length is required for both lapping and anchorage. This point is obviously of great practical importance and therefore the clarification of the relationship between laps and anchorages was chosen as one of the major objectives of the test programme.*" From a series of tests on beams without transverse reinforcement (stirrups) incorporating bars in contact splices, or a bar anchored mid-way between an adjacent pair of smaller diameter bars to simulate bar anchorage (a form of non-contact splice), they concluded that "*The tests indicate that there is no difference between the bond stresses which can be developed in a single bar anchorage and those which can develop in a lap*", confirming the conclusions of "*Orangun, Jirsa and Breen, who, from a very comprehensive study of the available data, were unable to detect differences between laps and single bar anchorages*".

Finally, referring to Fig. 2(b) it is also worth pointing out that Orangun et al. (1975) state that "*If alternate splices are staggered within a required splice length…the value of clear spacing* [meaning the same as clear distance] *at a critical section through the end of the splice may be taken without considering the continuous adjacent bars.*"

4.2 Contact versus non-contact lap splices

MacGregor and Wight (2005) have observed first hand from tests the development of concrete struts that form between lapped bars in non-contact splices. Their observations are also described in ACI (2003) and ACI (2005). According to ACI 318-05 (ACI 2005), contact and non-contact splices have the same design bond strength provided certain spacing requirements are met.

As already mentioned, this is based on the results of extensive research, e.g. ACI (2003). Hamad and Mansour (1996), whose work is referred to in ACI (2003) and contributes towards supporting the rule in ACI 318-05 described above, undertook a series of tests on nominally identical 600 mm wide flexural elements. The effect of systematically increasing the clear distance between lapped bars, starting with a contact splice, was investigated using 14, 16 and 20 mm diameter bars without any transverse reinforcement present in the region of the laps. The most relevant results of their tests are presented in Fig. 3, i.e. when the clear distance between adjacent lapping bars was less than the clear distance to the next bar in the adjacent lap.

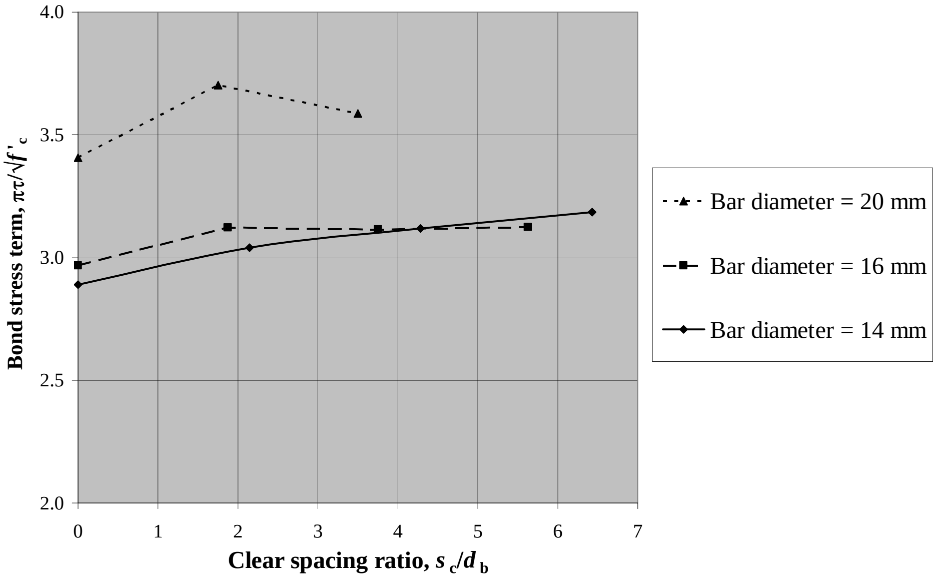


Figure 3 Results of flexural bond tests from Hamad and Mansour (1996)

In Fig. 3, the vertical axis represents the ultimate bond stress at failure (noting that the test elements were all designed to fail by bond), and the horizontal axis represents the clear distance between the bars. The bottom concrete cover to all of the bars, and the side cover to the outermost bars, remained constant at 20 mm in all of the tests. It is clear from these tests that there was a slight increase in the bond failure stress by introducing a gap of about 2 bar diameters between lapped bars, but the increase in strength compared to the contact spice condition (s_c/d_b=0) was insignificant in practice, for all of the bar diameters examined.

5. Typical safety factor using AS 3600–2001 lap splice design method

Splices formed between pairs of Class N reinforcing bars should not fail prematurely in tension or compression before the spliced reinforcing bars can at least satisfy their minimum strength and ductility requirements. For the purposes of this paper, it will be assumed that these performance requirements will be met provided that in a *real test*, a splice allows the bars outside the spliced region to reach a minimum tensile stress of 1.25 times the *nominal* yield stress, f_{sy}, of the bars before failing. This condition can be written as follows:

$$f_{u.test} \geq YSF \times f_{sy} \quad (2)$$

where $f_{u.test}$ equals the maximum tensile stress reached in the bars immediately outside the spliced region under uniform bending conditions; *YSF* is the yield stress factor; and f_{sy} equals the nominal yield stress of the deformed reinforcing bars (500 MPa for Class N bars). The value of *YSF*=1.25 is in accordance with the minimum requirements of ACI 318-05 for mechanical tensile splices between hot-rolled deformed reinforcing bars under non-seismic conditions in buildings. Testing of typical Class N reinforcing bars also indicates that by satisfying Eq. 2, the minimum ductility requirements for Class N reinforcing bars specified in AS/NZS 4671 (2001) should be satisfied, in particular that the uniform strain, ε_{su}, reached in the bars immediately outside the spliced region will be at least 5%. An approximate formula for calculating the factor of safety (FOS) of a splice in a slab or wall tested to failure in bending is given by Eq. 3 as:

$$\text{FOS} = \frac{1}{\phi} \times \frac{f_{\text{u.test}}}{f_{\text{sy.test}}} \times \frac{L_{\text{sy.t}}}{L_{\text{test}}} \times \frac{1.2G + 1.5Q}{G + Q} \quad (3)$$

It follows from Eqs 2 and 3 that an approximate target FOS for AS 3600, for arbitrary case G=Q, equals (1/0.8)×1.25×1.0×(2.7/2)=2.1. By way of example, some of the tests used by Orangun et al. and Walsh, viz. Ferguson and Breen (1965), have been analysed. Gilbert (2007b) analysed the same data (lower specimen numbers 1 to 9 in his Table 4) and computed an average FOS of only 0.94, thus claiming that the AS 3600–2001 method is unsafe. However, the authors believe Gilbert made a number of major errors when assessing the test data. By using Eq. 3 with G=Q, the average FOS in fact equals 2.2, just above the approximate target value of 2.1, implying that the method in AS 3600–2001 is sufficiently safe, and the spliced bars should also be ductile.

6. Conclusion

The background and useful improvements to the important formula for $L_{\text{sy.t}}$ in AS 3600 have been explained, and a brief safety assessment made that shows it is sound, and should continue to be used in its present form. Two major practical, economical benefits are that contact and non-contact splices may normally be treated as equivalent, and development and splice lengths are often the same. Another benefit is that transverse reinforcement is automatically accounted for.

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