STRENGTH AND DUCTILITY OF MECHANICALLY SPLICED BARS

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Synopsis. Mechanical couplers are used in Australia to splice together hot-rolled, Class N reinforcing bars. As a general principle, couplers must have sufficient strength to enable the spliced bars to elongate sufficiently while approaching ultimate load. If a splice forms a weak, rigid link, with its failure load significantly less than that of either of the attached bars, then it can be deduced that the overall response of the spliced bars will be brittle. It follows that the spliced bars would then not satisfy the minimum ductility requirements for reinforcing bars specified in the new joint Australian/New Zealand Standard AS/NZS 4671, "Steel Reinforcing Materials".

Previously in Australia, mechanical splices have only had to be strong enough to allow the stress in the bars to reach 1.1 times their nominal yield stress before failing. With the move to 500 MPa as the standard strength grade for reinforcing steels in Australia, the tensile strength of bars can often be significantly greater than 1.1 times 500 MPa. Therefore, spliced bars will have to be much stronger than was previously expected if they are to behave in a ductile manner. Realising this, design rules for mechanical splices have not been included in the new edition of the Australian Concrete Structures Standard, AS 3600:2001. It is anticipated that once the research reported herein (plus some additional research concerning serviceability issues) is completed, new rules will be incorporated in an amendment to AS 3600:2001 that will define minimum performance requirements for mechanical splices made between Australian 500 MPa, Class N reinforcing bars. Consideration is also given briefly in the paper to the classification and design of brittle mechanical splices. Development of such design rules would allow coupler manufacturers time to assess, and possibly modify or phase out these products. The rules could also be used to assess the safety of existing structures.

1.0 DESIGN OF MECHANICAL SPLICES TO AS 3600: 1994

The minimum strength requirements for welded and mechanical splices between reinforcing bars are defined in Clause 13.2.2 of the recently superseded Australian Concrete Structures Standard AS 3600: 1994 [1]. The splice had to be designed, or shown by testing, to be capable of developing a stress, in tension or compression, not less than $1.1f_{sy}$, where f_{sy} is the nominal or design yield stress of the weaker bar at the splice. The reinforcement was hot-rolled, deformed Y-bar that satisfied the requirements of AS 1302:1991 [2] with a nominal yield stress, f_{sy}, of 400 MPa. This meant, therefore, that a splice could legitimately fail at a bar stress of only 440 MPa, and no conditions were placed on the ductility of the failure mode.

Also, there were no conditions placed on the performance of mechanical splices under serviceability conditions when, depending on the type of coupler, longitudinal slip of the bars in the coupler may become an issue, particularly with regard to crack control. However, this is beyond the scope of this paper.

In accordance with Table 10 of AS 1302, the minimum tensile strength of Grade 400Y bar was $1.1YS$, where YS is the yield stress as determined from the tensile test being performed. Assuming a normal distribution of yield stress, YS, for 400Y bar when it was produced gives rise to the solid bell curve in Fig. 1. The mean value of this curve is $1.15f_{sy}$=460 MPa, which itself is greater than $1.1f_{sy}$=440 MPa which is shown in Fig. 1 as a heavy solid vertical line. Moreover, the dashed bell curve is intended to represent the tensile strength of the bars, simplistically assuming a constant value of 1.15 for the tensile-strength-to-yield-stress ratio, i.e. $TS=1.15YS$. It is clear from Fig. 1 that if a splice were only of minimum strength, then the probability of breaking the bars rather than failing the splice in a test would be virtually zero, i.e. $\Pr(TS \leq 440\text{ MPa}) \approx 0$. It follows that the coupler would almost certainly have an adverse effect on the strength and ductility of the spliced bars.

Further inspection of Fig. 1 shows that there is a reasonably high probability that if a minimum strength splice were used, then the bars would not even have yielded before the splice would have failed. (This probability equals the area under the *YS* bell curve to the right of the heavy solid vertical line.) In this case, if the splice failed suddenly when it reached its maximum strength, then the failure mode of the spliced bars would have been brittle. This is because on average the bars would have strained less than the average yield strain, ε_{sy}=0.23% (assuming that the bars displayed a distinct yield point, i.e. they were not cold-worked, for example by de-coiling). The effect that a splice of inferior strength can have on the behaviour of a pair of spliced bars is explained in more detail in Section 5 using a simple behavioural model.

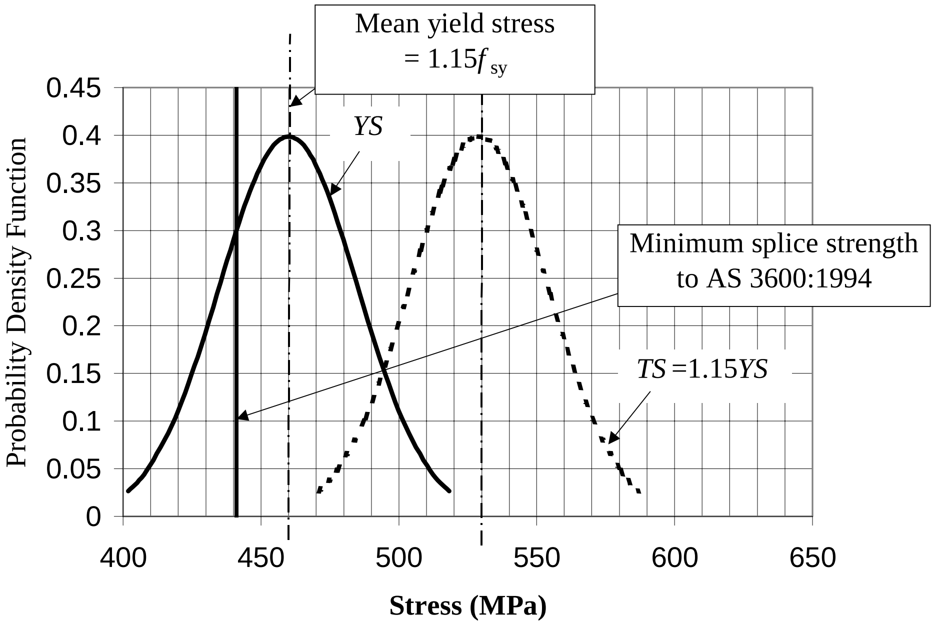


Fig. 1 Estimated strength of superseded Australian 400Y bar

The discussion above explains why the authors first became concerned about the design provisions in AS 3600: 1994 for welded and mechanical splices, which ultimately led to the rules being withdrawn and not included in AS 3600: 2001 [3].

2.0 STRENGTH AND DUCTILITY OF CLASS N REINFORCING BARS

The minimum properties of Class N, normal ductility reinforcing bars are defined in the new joint Australian/New Zealand Standard AS/NZS 4671 for steel reinforcing materials [4]. The bars are available in standard diameters of 10 to 40 mm. In accordance with sampling procedures described in AS/NZS 4671, the bars must have a minimum tensile-to-yield-stress ratio, R_m/R_e, of 1.08 and a minimum uniform elongation or strain, ε_{su}, of 5.0%. (Uniform elongation is the strain at peak stress on an engineering stress-strain curve, which corresponds to the onset of necking.)

Patrick et al. [5] explain that Class N reinforcing bars can be used without restriction in Australian building structures designed in accordance with AS 3600:2001. In contrast, low ductility reinforcing steel, viz. Class L mesh, cannot be used in all situations, for example in beams and slabs designed assuming a significant amount of negative or downward moment redistribution at the strength limit state. For example, Class L mesh should not normally be assumed to act as main reinforcement at ultimate load in slabs or beams designed plastically. In contrast to Class N bars, Class L mesh only has to have a minimum tensile-to-yield-stress ratio, R_m/R_e, of 1.03 and a minimum uniform elongation or strain, ε_{su}, of 1.5%.

Similar to Fig. 1 for 400Y bar, estimates of the distribution of yield stress and tensile strength of hot-rolled 500N bar currently produced in Australia are shown in Fig. 2. This information is of fundamental importance to properly design a mechanical or welded splice. This matter will be discussed in Section 5.0. It is equally important to know the shape of the tensile stress-strain curve up to the onset of necking, i.e. peak stress. For the purpose of this paper, it will be assumed that the bi-linear curve shown in Fig. 3 can be used for this purpose [3,6], with ε_{su}=10% being a reasonable lower-bound estimate that is often well exceeded, at least for TEMPCORE® straight bar.

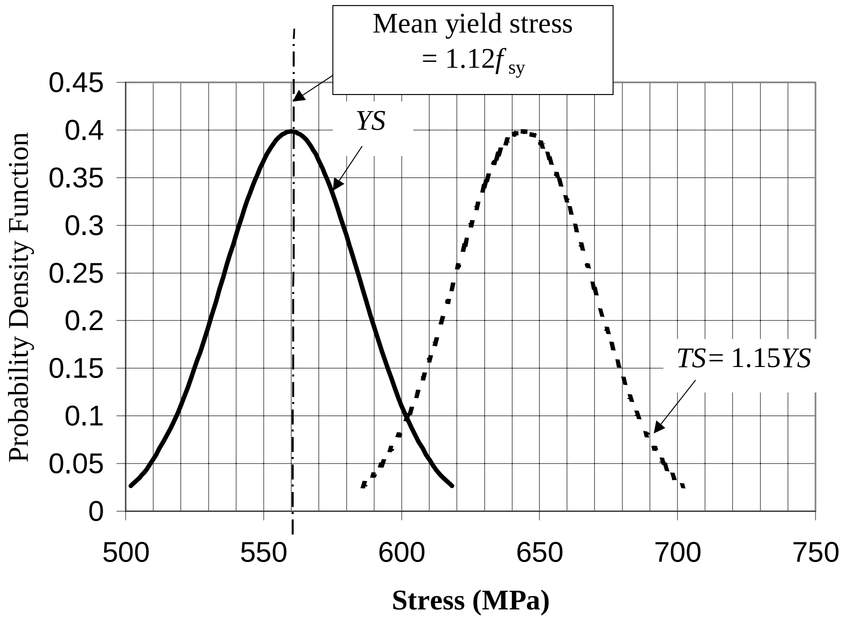


Fig. 2 Estimated strength of new Australian 500N bar

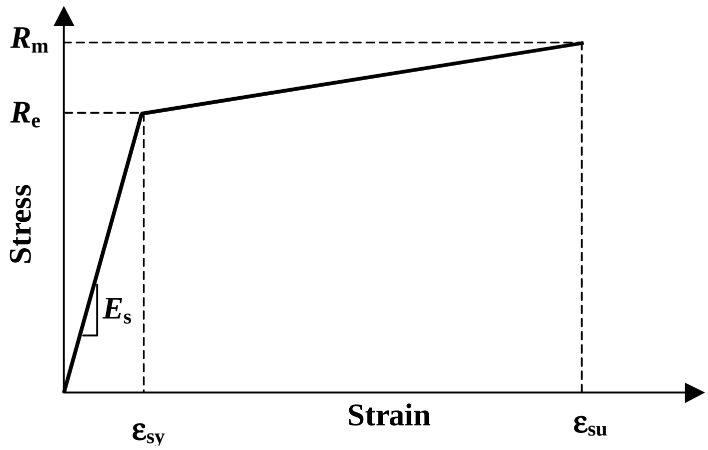


Fig. 3 Approximate stress-strain curve of new Australian 500N bar [3,6]

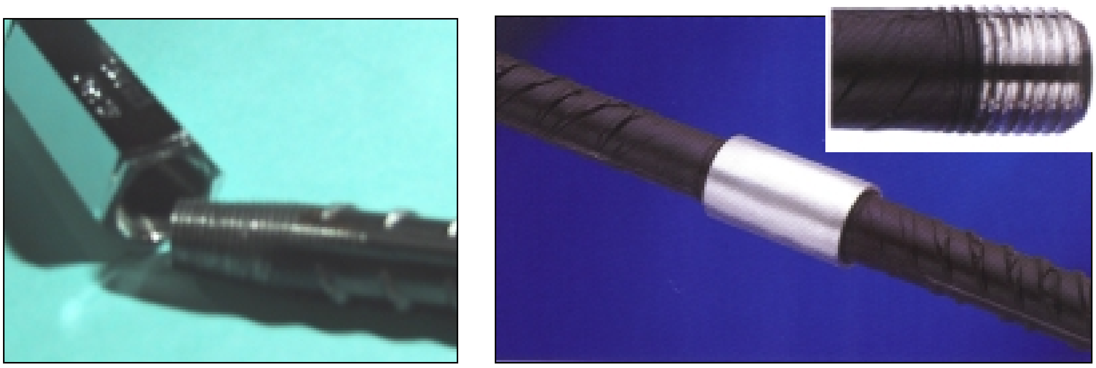
3.0 MAIN TYPES OF MECHANICAL COUPLERS USED IN AUSTRALIA

Mechanical couplers are proprietary items that come in a wide variety of forms. It is beyond the scope of this paper to review all of these. By far the most popular types of couplers used in Australia are all threaded, some of which are briefly described below.

The type of coupler shown in Fig. 4 is used to join together hot-rolled 500 MPa TEMPCORE® bars that have a continuous, right-hand coarse thread that also serves as the bar deformations. The bars are intended to be tightened up snuggly on site, to remove any slack in the connection. This way the deformations on the bars are tightly engaged with the coupler threads. An end stop in the middle of the coupler is intended to assist in this process. Lock nuts are available which are sometimes used to increase the precompression between the bar and coupler threads before the concrete is cast. The normal mode of failure when this product is tested in tension is for the bars to fracture. This is because the coupler has been designed to withstand a force corresponding to a stress in the bars of at least $1.6f_{sy}=1.6\times500=800$ MPa [7], which as can be seen from Fig. 2 is almost certainly stronger than any 500N bar produced in Australia.

Fig. 4 Popular type of coarse-threaded coupler used in Australia [7]

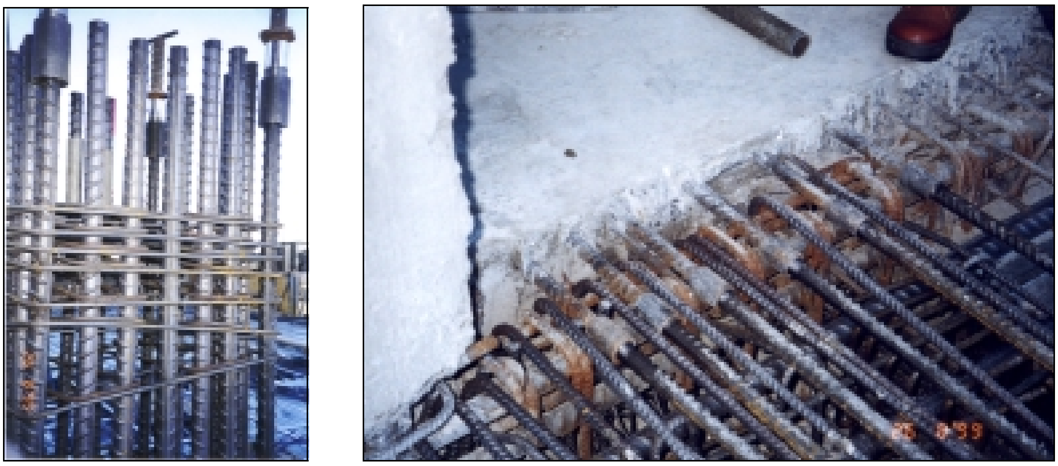
The types of couplers shown in Fig. 5 are both fine threaded. The coupler in Fig. 5(a) has a tapered thread cut into the end of the bar. The bar is installed into the coupler by turning the bar a set number of revolutions. The normal mode of failure for this splice is for the threads on the bar to strip. Bar fracture does not occur. However, for the type of splice that is shown in Fig. 5(b), in which the bar ends have been enlarged by cold forging, end failure of the parallel threads can be designed against and bar fracture normally occurs.



(a) Tapered thread cut into bar [8,9]   (b) End of bar forged, then threaded [10]

Fig. 5 Popular types of fine-threaded couplers used in Australia

Typical applications for threaded couplers are shown in Fig. 6, which have advantages over some other types of mechanical couplers, such as being able to be installed with minimal effort in very confined situations. Of interest in Fig. 6(a) is that the couplers all occur at one cross-section. In Fig. 6(b) it can also be seen that they are likely to be at critical locations of maximum bending moment if immediately adjacent to supporting beams or walls (again noting, in Fig. 6(b) all the main bars are spliced at one location).



(a) Column bar splicing (b) Splicing of all slab main top bars

Fig. 6 Typical coupler applications

4.0 BRIEF REVIEW OF OVERSEAS DESIGN PROVISIONS FOR MECHANICAL SPLICES

The design provisions for mechanical splices in AS 3600:1994 were intended for non-seismic applications. They were much less demanding than comparable provisions in a number of other national Standards, and as a result it has been possible in Australia to use couplers that may have less strength than those used overseas.

In British Standard BS 8110: Part 1 [11], the tensile strength of coupled hot-rolled bars has had to be at least 1.15 times the nominal yield stress, f_{sy}. The intention has been that the coupler should be stronger than the bar [12]. In practice the requirement in BS 8110: Part 1 has only meant that the strength of a splice at least equals the required minimum tensile strength of the bars. As a consequence, it has been conceded that it may not be possible to force failure outside a coupler when the bar strength exceeds the minimum.

Fig. 7 Test set-up for measuring end slips and extension over coupler

Another requirement in BS 8110: Part 1 has been to ensure that the permanent elongation across the coupler does not exceed 0.1 mm after the bars have been stressed to $0.6f_{sy}$ (see Fig. 7). This elongation arises due to slip of the bars relative to the coupler. It appears likely that the value of 0.1 mm was chosen because it was considered to be sufficiently smaller than the normal upper characteristic limit of 0.3 mm for crack widths in buildings, and does not appear to be supported by the results of research [12].

In NZS 3101: Part 1 [13], mechanical splices are normally required to be stronger than the breaking strength of the bars. This may require the coupler housing to be very strong indeed, and for tests to be done using very high-tensile bars to demonstrate conformance [7]. Unfortunately, provisions explaining to manufacturers how they must test their products for conformance are not contained in NZS 3101: Part 1. The New Zealand Standard also allows mechanical splices with less capacity to be used in "partial splices" provided a number of conditions are met, i.e. they are staggered, can develop at least twice the calculated force in the bars (i.e. bars have excess capacity), etc.

In ACI 318 [14,15], a "full" mechanical splice must develop a stress of at least $1.25f_{sy}$ in the bars. This is so as to "ensure sufficient strength in splices so that yielding can be achieved in a member and thus brittle failure avoided", and "the 25 percent increase above the specified yield strength was selected as both an adequate minimum for safety and a practicable maximum for economy". Referring to Fig. 2, it is clear that if a particular type of coupler was used that failed at $1.25f_{sy}$ =625 MPa, as required by ACI 318, then it would still be unlikely that Australian-produced 500N bars would break. Thus, the intent of BS 8100: Part 1 and NZS 3101: Part 1 would still not be met.

A problem with all of the design provisions cited in the Standards above is that they do not cater for types of mechanical splices that can never be stronger than the bars. Neither do the provisions, as expressed, explain how to interpret the results of a test involving a bar with a tensile strength less than the prescribed minimum stress that has to be achieved. However, a number of European Standards cater for these products and the situation of a weak bar, e.g. [16]. Their provisions define a minimum ductility requirement, viz. typically 3-4% uniform elongation, which has to be satisfied in tensile tests for the splice to be deemed a suitable full strength splice. Eurocode 2: Part 1, however, does not contain any specific design provisions for mechanical splices [17].

5.0 BEHAVIOURAL MODEL FOR MECHANICALLY SPLICED BARS

The effect that splice or coupler strength can have on the ductility of a Class N bar with a stress-strain curve of the form shown in Fig. 3 can be readily examined using a simple behavioural model of a pair of spliced bars in direct tension.

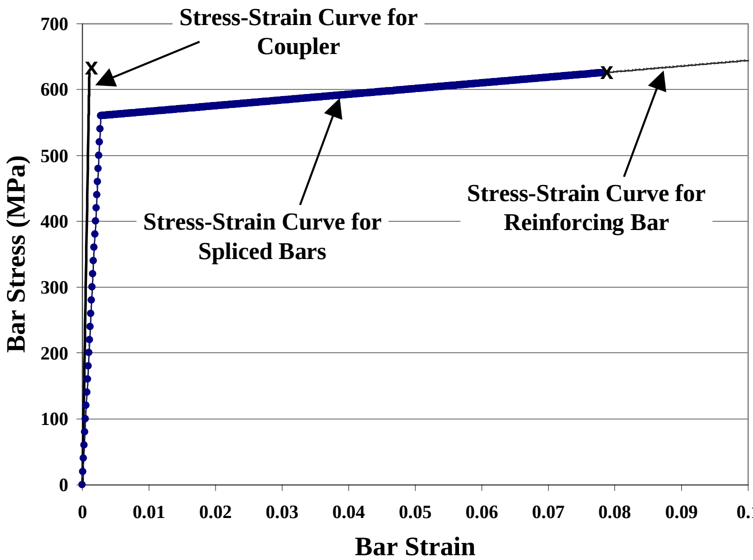


Fig. 8 Effect of premature failure of coupler on spliced bar ductility

Referring to Fig. 2, consider an average Australian Class N bar with a mean yield stress of 560 MPa, a tensile-to-yield-stress ratio of 1.15 and a uniform elongation of 10 percent. Its stress-strain curve is shown in Fig. 8 and is identified as "Stress-Strain Curve for Reinforcing Bar". It has been assumed that the coupler connecting the bars breaks suddenly when the stress in the bars reaches $1.25f_{sy}$=625 MPa, as per ACI 318 (see "Stress-Strain Curve for Coupler"). It is apparent from the "Stress-Strain Curve for Spliced Bars" in Fig. 8 that the ductility of the spliced bars has been significantly reduced with the tensile-to-yield-stress ratio now becoming 1.11 and the uniform elongation less than 8 percent. However, the ductility of the spliced bars still exceeds the minimum requirements for Class N bars in Australia (see Section 2), so its performance can still be considered as satisfactory. The strength of the coupler has to remain above about 600 MPa (or $1.2f_{sy}$) for this to still be the case for an average bar.

Similar graphs can readily be produced for other scenarios of coupler strength and bar yield and tensile strength. By making assumptions about the effective cross-sectional area of the coupler, its length and its modulus of elasticity, it is possible to estimate the elongation that occurs over the coupled region of the bars for any particular gauge length. This can be used to analyse results from tests like that shown in Fig. 7, but a detailed discussion of this topic is beyond the scope of this paper.

6.0 BEHAVIOURAL MODEL FOR THREADED MECHANICAL SPLICES

When the threads in a splice fail rather than one of the bars breaking, the threads near the ends tend to fail first. A theoretical explanation of this phenomenon is given in this section, where it is shown that the shear stresses are greatest at the coupler ends. The theory can be readily adapted to cover tapered bars, and in this case even TEMPCORE bars can be modelled with their non-homogeneous steel properties (hardest steel in the region of their outer surface). The model can also be used to predict slip. Then it is possible to determine the effect of initial take-up in the threads, and also the effect of precompression if any.

6.1 Idealised Theoretical Model

One half of a threaded coupler subject to a tensile force, T, is idealised in Fig. 9. A simple theoretical model for the behaviour of this mechanical splice can be obtained by treating the threads as a continuum element of thickness, t, and length, l, with appropriate uniform material properties.

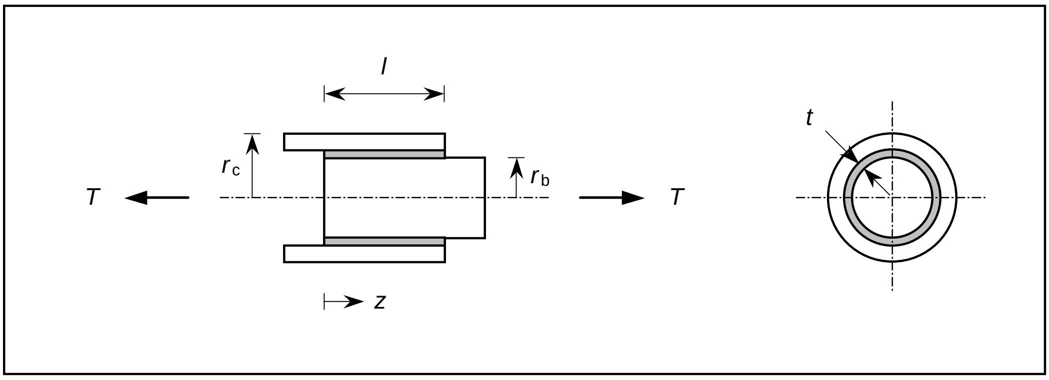


Fig. 9 Idealised theoretical model for one half of a threaded coupler

6.2 Equilibrium

The governing differential equation of equilibrium is given by:

$$A_c \frac{d\sigma_c}{dz} + A_b \frac{d\sigma_b}{dz} = 0 \tag{1}$$

in which

$$\frac{d\sigma_c}{dz} = \frac{2\pi(r_b + t/2)}{A_c}\tau \tag{2}$$

and

$$\frac{d\sigma_b}{dz} = -\frac{2\pi(r_b + t/2)}{A_b}\tau \tag{3}$$

6.3 Constitutive Relationships

The usual constitutive relationships for steel are adopted, with the exception of the effective uniform shear modulus for the continuum thread element, which may be represented as a proportion of the standard value, as given by:

$$G' = kG \tag{4}$$

in which k must be between zero and unity.

6.4 Compatibility

The compatibility at each longitudinal cross-section of the axial and shear strains can be expressed as:

$$\frac{d\tau}{dz} = \frac{G'}{Et}(\sigma_b - \sigma_c) \tag{5}$$

6.5 Boundary Conditions

For the model shown in Fig. 9, the boundary conditions are given by:

$$z = 0: \qquad \sigma_b = 0 \qquad \sigma_c = \frac{T}{A_c} \tag{6}$$

$$z = l: \qquad \sigma_b = \frac{T}{A_b} \qquad \sigma_c = 0 \tag{7}$$

6.6 Failure Criteria

A threaded mechanical splice may fail due to yielding of the bar or coupler in tension, or yielding of the threads in shear. For pure shear, the appropriate yield stress is:

$$\tau_y = \frac{1}{\sqrt{3}}\sigma_y \tag{8}$$

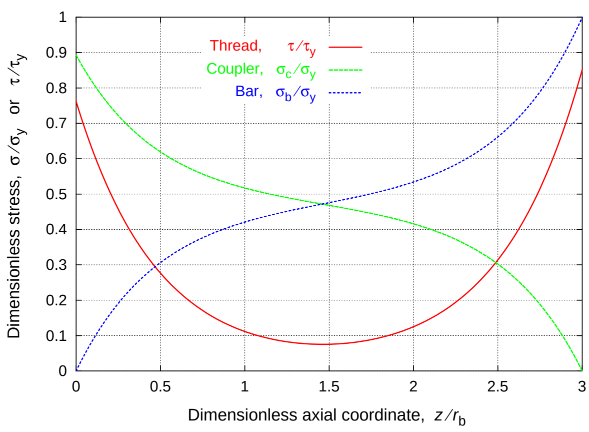


Fig. 10 Stress distributions for one half of a threaded coupler

6.7 Numerical Solution

The governing differential equation may be solved numerically with Euler's method using a shooting technique to satisfy the boundary conditions. Typical results are given in Fig. 10 for a threaded mechanical splice with the following parameters:

$$\begin{aligned} r_c &= 1.6 r_b \qquad & \sigma_{yb} &= \sigma_{yc} \\ t &= 0.2 r_b & k &= 0.5 \\ l &= 3 r_b & T &= A_b \sigma_{yb} \end{aligned} \tag{9}$$

The critical cross-sections for the threaded element are clearly at each end of the thread, namely at z=0 and z=l, confirming experimental observations of failure regions.

7.0 DEVELOPMENT OF MINIMUM PERFORMANCE REQUIREMENTS FOR SPLICED BARS

New minimum performance requirements for mechanical and welded splices are currently under development for inclusion in AS 3600. This work is being undertaken by the Standards Australia BD/2/1 "Ductility" subcommittee. Engineers from the major manufacturers of mechanical and welded splices are members of the subcommittee. Serviceability issues are also being addressed, but are not discussed here.

It should be clear from the discussion in Sections 4 and 5 that, given the different types of behaviour of threaded couplers, it is not simply a matter of deciding upon the minimum bar stress level (e.g. $1.25f_{sy}$ in ACI 318) at which a splice may fail. It may be impractical to require that a mechanical splice will not affect the performance of spliced bars. Strength, ductility and stiffness may be reduced to some extent, but obviously this needs to be controlled. Therefore, it is possible for some types of splices to fail instead of the bar, and yet overall the spliced bars still behave satisfactorily. The effect that critical bar properties, e.g. tensile strength, can have on behaviour needs to be considered. Bars with different tensile strengths may need to be tested, not just "strong" bars at the high-end of bar manufacturers' tensile data, depending on the failure mode involved. Bar diameter is an important variable for all types of couplers.

It is proposed that the ductility of spliced bars should normally at least meet the minimum ductility requirements for Class N bars assumed in AS 3600, i.e. those specified in AS/NZS 4671. Otherwise the splices might be classified as brittle. Rules for potentially brittle splices have already been included in Standards, e.g. partial splices in NZS 3101: Part 1. It may be necessary to include similar rules in AS 3600, since this would allow coupler manufacturers time to assess, and possibly modify or phase out these products. They would also allow the safety of existing structures to be assessed.

8.0 DESIGN IMPLICATIONS FOR WELDED AND OTHER SPLICES

There are important design implications for welded and indeed any type of splice, that follow from the minimum performance requirements proposed in Section 7. In particular, great care needs to be taken when comparing rules from different national and international Standards. If the rules are soundly based, then account also needs to be taken of the actual tensile properties of the steels assumed in their derivation, and not just of their nominal values, when evaluating any differences between the rules.

Sudden failure of splices should be avoided if they are used in critical regions where the tensile stresses in the bars are a maximum. Detailed information is required about the properties of the reinforcing steels that will be used, if this is to be confidently achieved.

9.0 CONCLUSIONS

Much attention has been given in recent times towards establishing minimum ductility requirements for reinforcing bars and mesh used in Australia. A further step forward on this path has been taken in this paper by considering minimum ductility requirements of spliced Class N reinforcing bars. The tensile properties of the bars must be known, since this can significantly affect the failure mode depending on the strength of the splice. It appears to be impractical to insist that failure of a splice should never occur. It has been proposed that where splices are to be used in critical regions where bar stresses are a maximum, then the ductility of spliced bars should normally at least meet the minimum ductility requirements for Class N bars specified in AS/NZS 4671 and assumed in AS 3600. The need for these requirements to be met by mechanical splices has been considered in this paper, and the same principles apply for welded or any other type of splice. Further work is required before new design rules can be proposed for possible inclusion in AS 3600. Serviceability design issues are also being addressed in detail.

10.0 REFERENCES

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