A design stress strain curve for prestressing strands

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| **Abstract**Section 8 of AS 5100.5:2017 mandates the use of equilibrium and strain compatibility considerations to calculate the ultimate limit state (ULS) moment capacity for prestressed concrete sections. However, the standard does not provide a design stress-strain curve for prestressing strands. Rather, equation 8.1.7(1) is provided to estimate the stress in bonded tendons at ULS but with a condition placed on the effective prestress for its validity. In practice, many designs may not meet this requirement rendering the use of this equation invalid. Furthermore, the derivation of Equation 8.1.7(1) has been based on sections with a single layer of prestressing and its application for sections with more distributed prestressing is unclear. Nonetheless, AS 5100.5:2017 together with AS 4672.1-2007 provide strength and elongation limits that prestressing strands need to comply to. It has been typical design practice to use a ‘model’ stress-strain curve for strands, based on the afore-mentioned compliance limits, although there has been no consistency as to the form of these curves across industry. As such, the same prestressing can result in different moment capacities depending on the form of the curve. To provide a consistent basis for calculating the ULS moment capacity of prestressed beams of its bridge stock, Main Roads WA has recently mandated the use of ‘design’ stress-strain curves for strands. This paper discusses these which are based on the breaking and proof strengths as per AS 4672.1-2007 and an adopted failure strain of 5%. The proposed curves are also compared to stress-strain formulations found in several international design standards and widely cited publications. The sensitivity of the ULS moment capacity to the form of the stress-strain curve as well as the adopted failure strain is quantified using several as-constructed Teeroff beams. Comparison of the proposed formulations is also made to stress-strain test data provided by industry. **Keywords:** prestressing, stress-strain curve, bridges, AS 5100.5:2017, moment capacity |

# Background

Even though Section 8.1.2 of AS 5100.5:2017 specifies the consideration of strain compatibility for flexural strength calculations of prestressed concrete members, the code does not explicitly specify a stress-strain curve for prestressing strands. Rather, Cl 3.3.3 of AS 5100.5:2017 only states that a stress-strain curve for prestressing strands shall be determined from appropriate test data without providing any further guidance.

For non-prestressed reinforcement an elastic-plastic model is routinely assumed for flexural capacity calculations. However, the use of such a model is not representative for prestressing strands and can lead to considerably conservative capacities if based on the yield strength of prestressing strands (taken as the 0.1% proof strength in AS 5100.5:2017). This is so since, as per AS 5100.5:2017 the 0.1% proof strength is specified to be taken as only 0.82 fpb (fpb ≡ breaking strength of the strand).

In lieu of a stress-strain curve, AS 5100.5 CL 8.1.7 specifies an approximation in the form of an equation, reproduced in Equation 1 below, to calculate the stress in the strands at the ultimate limit state (ULS) flexural capacity. Note that the discussion of this paper is limited to sections with no passive reinforcement (i.e Ast = Asc = 0 in Equation 1)

|  |  |
| --- | --- |
| $$σ\_{pu}= f\_{pb}\left(1-\frac{k\_{1}k\_{2}}{γ}\right)$$ |  1 |
| where |
| k1 | = | 0.4 if fpy/fpb < 0.9 or 0.28 otherwise |
| k2 | = | $\frac{1}{b\_{ef}d\_{p}f\_{c}^{'}}\left[A\_{pt}f\_{pb}+\left(A\_{st}-A\_{sc}\right)f\_{sy}\right]$ , definition of terms as per AS 5100.5:2017 |
| fpb |  | Breaking strength of the strand |
| γ |  | Ratio of rectangular stress block height to neutral axis height as per Cl 8.1.3 of AS 5100.5 |
| σpu |  | Stress in strand at the ULS flexural capacity |

Equation 1 first appeared in ACI318-1983 and remains in use in the current version of ACI318 as well. It is also accompanied by the condition that the effective prestress (fpe) should be greater than 0.5 fpb for its use. The basis for adopting this equation is explained by Mattock1 where the σpu values predicted by Equation 1 were compared against those predicted by strain compatibility analyses of rectangular sections for different values of fpy\*, f’c and Aptfpb/ (b dp f’c) ratios (as well as various amounts of passive compression and tension reinforcement). Note that fpy\* is the strain in the prestressing strand at 1% strain. A stress-strain curve for Grade 270 ksi (1860 MPa) strand satisfying the minimum strength limits as per the ASTM specifications at the time with an assumed failure strain of 5% and following the form of the power law equation given by Equation 2 was considered for this exercise. The stress-strain curves used by Mattock1 are shown in Figure 1. An effective prestress of 0.6fpb was assumed for these calculations which is consistent with the criteria that is specified in AS 5100.5:2017 for the use of Equation 1. As Mattock1 states, this condition (i.e. fpe ≥ 0.5 fpb) was also present in the pre-1983 versions of Equation 1 (from ACI318-1963 onwards). He further states that this condition was likely specified based on comparing the predictions of the equation with the corresponding experimentally measured values of several series of tests. Details of these tests can be found in the University of Illinois Bulletin 4642.

|  |  |
| --- | --- |
| $$f\_{ps}= ε\_{ps}\left[A+\frac{B}{\left\{1+\left(Cε\_{ps}\right)^{D}\right\}^{^{1}/\_{D}}}\right] $$ |  2 |
| Where |
| fps | = | Stress in prestressing strand in MPa |
| εps | = | Strain in prestressing strand (strain at fpb was taken as 0.05) |
| A, B, C, D | = | 5214.7, 184391.2, 115.2, 7.002 for fpy\*/fpb = 0.852872.8, 186733.1, 108.7, 9.080 for fpy\*/fpb = 0.90 |

Figure 1 Stress-strain curves used by Mattock1 for development of Equation 1.

The use of equation 1 to calculate the stress in the prestressing at the ULS has several drawbacks. Firstly, it does not allow the strain level in the prestressing at the ULS, which is compatible with the assumed failure strain in the extreme concrete fibre (i.e. corresponding to concrete crushing), to be determined. As such, the use of Equation 1 inherently assumes that the strain in the prestressing is less than the breaking strain of the strand at ULS. While this is likely to be the case in practice, it would be diligent to check this explicitly to ensure that the ULS failure indeed corresponds to concrete crushing. As shown in later sections of this paper, depending on the failure strain assumed for the analysis and for sections of higher concrete strengths, the strand strains that are needed for a compression controlled flexural capacity (i.e. by concrete crushing) may be greater than the assumed failure strain. Equation 1 also strictly cannot be used for when the effective prestress becomes less than 0.5fpe, a scenario which is not uncommon. For example, for an initial jacking stress of 70%fpb, a 30% loss results in an fpe of 0.49fpb. It may indeed be the case that the equation remains an acceptable approximation for lower values of prestress as well, but this does not seem to have been investigated in the work that formed the basis of Equation 1 (which was discussed previously). Furthermore, Equation 1 is based on considering the prestressing as lumped at its centroid which may not always reflect reality, especially for larger sections where several layers of prestressing may be used resulting in differing stresses between layers. The strain compatibility analyses which formed the basis of Equation 1 also utilised the equivalent rectangular stress block defined in ACI318-1983. The stress block that is specified in AS 5100.5:2017 differs from that in the current version of ACI318 especially for concrete strength grades greater than 50 MPa.

It should also be noted that the stress-strain curves used for the development of Equation 1 (i.e. shown in Figure 1) are only strictly applicable to Grade 1860 MPa strands. However, in Australia, several differing grades of strands are used, as detailed in AS 4672.1:2007. These strands differ in their ultimate breaking strengths as well as in the fpy\*/fpb ratio, compared to those of the curves in Figure 1. Equation 1 inherently assumes the use of the same grade of strand (i.e. 1860MPa) and does not cater explicitly for situations where strands of different grades may be used. While such scenarios are not common, they do occur. For example, the Main Roads WA standard prestressed planks use 12.7mm and 15.2mm strands of differing grades in combination.

In addition, as described by Mattock1, during the development of Equation 1 it was observed that it does not give consistently conservative results compared to the strain compatibility analyses, with some stress predictions being higher than those of the corresponding strain compatibility runs. Rather the adoption of Equation 1 in ACI318 was justified by Mattock1 based on the consistent close agreement that was observed rather than a consistent conservativeness.

Given the foregoing context, to overcome the afore-discussed limitations, Main Roads WA has proposed a stress-strain curve for prestressing strands to use when calculating flexural capacities of prestressed sections, which has been published in the Main Roads WA Bridge Branch Design Information Manual (BBDIM)3. The intention of this proposal is also to provide a consistent methodology for all designs, as it has been observed that different stress-strain curve formulations are being used by designers for strands, in lieu of Cl 8.1.7, for Main Roads WA projects in Western Australia.

# Proposed stress-strain formulation

Even though AS 5100.5:2017 does not specify a stress strain curve for prestressing strands, AS 4672.1:2007 does specify minimum compliance requirements for tensile properties of a range of different prestressing strands. These include modulus of elasticity, 0.1% proof load, 0.2% proof load, minimum breaking load and total elongation at failure. These properties are tabulated for three commonly used strand types in Table 1.

Table 1 Properties for three commonly used strand types extracted from AS 4672.1

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Strand nominal diameter mm | Nominal tensile strength MPa | Nominal cross sectional area Anom mm2 | Minimum characteristic loads kN | Modulus of elasticity E GPa | Elongation at maximum load εpb |
| 0.1% proof load (F0.1%) | 0.2% proof load (F0.2%)  | Minimum breaking load (Fpb) |
| 12.7 | 1870 | 98.6 | 151 | 156 | 184 | 195 +/- 10  | > 3.5% |
| 15.2  | 1830 | 143 | 214 | 222 | 261 |
| 15.7 | 1860 | 150 | 240 | 249 | 279 |

For each respective strand type, the values in Table 1 can be used to define 3 distinct points (Points 1 to 3) that lie on a stress strain curve just satisfying the limits specified in AS 4672.1. These 3 distinct points are noted qualitatively in Table 2. The most conservative stress-strain curve that can be formulated using these three points is to construct a piece-wise linear curve between them. This is so since all conforming prestressing strands will satisfy these minimum strengths and as such the actual stress-strain curves will always lie above this piece-wise multi-linear approximation. The portion of the curve for strains less than ε0.1% can be approximated by recognising that the gradient of the initial linear elastic portion of the curve (which is commonly termed as the proportional region of stress-strain curves of strands) is defined by the modulus of elasticity (E) and approximating the end of the proportional region by extending back a line defined by Points 2 and 1 to obtain its intersection with the initial linear portion (i.e. thereby defining Point 4 in Table 2). It should be noted that constructing a stress-strain curve in this manner is also consistent with Cl 3.3.3 of AS 5100.5:2017 as it is in conformance with, albeit conservatively, with test data (as it is based on minimum compliance requirements for such test data).

Table 2 Points on stress strain curve based on AS 4672.1 minimums

|  |  |  |
| --- | --- | --- |
| Point | Strain | Stress |
| Point 1 | $$ε\_{0.1\%}= 0.001+ ^{f\_{0.1\%}}/\_{E}$$ | $$f\_{0.1\%}= ^{F\_{0.1\%}}/\_{A\_{nom}}$$ |
| Point 2 | $$ε\_{0.2\%}= 0.002+ ^{f\_{0.2\%}}/\_{E}$$ | $$f\_{0.2\%}= ^{F\_{0.2\%}}/\_{A\_{nom}}$$ |
| Point 3 | εpb (assumed to be 5%) | $$f\_{pb}= ^{F\_{pb}}/\_{A\_{nom}}$$ |
| Point 4 |  $ε\_{4}=\frac{ε\_{0.1\%}- f\_{0.1\%}\left\{\frac{\left(ε\_{0.2\%}- ε\_{0.1\%}\right)}{\left(f\_{0.2\%}- f\_{0.1\%}\right)}\right\}}{1-E\left\{\frac{\left(ε\_{0.2\%}- ε\_{0.1\%}\right)}{\left(f\_{0.2\%}- f\_{0.1\%}\right)}\right\}}$ | $$σ\_{4}=Eε\_{4}$$ |

The stress-strain curves obtained in this manner for strands of diameters 12.7mm, 15.2mm and 15.7mm are shown in Figure 2. These curves are currently published in the Main Roads WA Bridge Branch Design information manual which is publicly available online. Note that Grade 1830 strands has been considered for the 15.2 mm case as that is the most used grade for 15.2mm strands in WA. Although not published guidance, stress-strain curves for other strands given in AS 4672.1 can also be constructed following the same rationale as discussed previously. It should be noted that for the stress-strain curves shown in Figure 2, the failure strain corresponding to the minimum breaking strength (fpb) has been taken to be 5% rather than the 3.5% min specified in AS 4672.1. In general, taking a larger failure strain results in more conservative flexural capacities (since for a given strain the stress is less). From test data shared with Main Roads WA by prestressing strand suppliers, it was observed that the failure strains achieved in the tests were generally much larger than the minimum of 3.5%. For example, this can be clearly seen in Figure 3 which shows the distribution of experimentally obtained failure strains in sample long term quality (LTQ) testing data shared upon request by SANWA Pty Ltd. The corresponding statistics are given in Table 3. Even though the average and upper characteristic values were greater than 5% for all three stand types for which LTQ data was supplied (as can be seen from Table 2) 5% was chosen to be a reasonable failure strain for the purposes of stress-strain curves for use in design/assessment. As can be seen in Figure 4 and Table 3, which compares the proposed curves against LTQ testing strength data, it was felt that given the test strengths that had been achieved were notably greater than the AS 4672.1 specified compliance minimums, taking εpb to be in the range of the mean/characteristic values given in Table 2 would result in unnecessarily conservative flexural capacities. The sensitivity of calculated flexural capacities to the assumed failure strain is discussed later in this paper.

It should be noted that a 5% failure strain has also been stated as a reasonably conservative assumption for the failure strain of prestressing strands by Skogman et al4 and Mattock1. Devalapura and Tadros5 also specified a failure strain of 5% in their proposed stress-strain curve for Grade 1860 MPa prestressing strands.

It should be noted that the stress-strain curves could have been based on taking εpb equal to 0.035 which is the minimum specified in AS 4672.1:2007. However, adopting this minimum value for εpb would be the most favourable assumption in relation to the ULS flexural capacity and as such this approach was not adopted. In addition, if the stress-strain curves were constructed based on a failure strain of 0.035, then, as will be seen from the discussions in later sections of this paper, this can result in an ULS capacity solution governed by concrete crushing not being possible since the required strain demand in the strands will be greater than 0.035. This could be mitigated by adopting a plateau of fpb for strains larger than 0.035 in the stress-strain curve though in that case, the curves will not be consistent with the concept of a ‘breaking’ strain.

Since Equation 8.1.7 of AS 5100.5:2017 was developed based on the stress-strain curves shown in Figure 1, it would seem reasonable to make the argument that those stress-strain curves can simply be adopted instead of those proposed in Figure 2.

However, the curves shown in Figure 1 is for a particular grade of strand i.e. Grade 1860MPa and is thus, strictly, not applicable to all grades of strand addressed by AS 4672.1:2007. On the other hand, the proposed methodology allows stress-strain curves to be constructed for all strand types referred to in AS 4672.1 Nonetheless, for Grade 1860 strand, the curves shown in Figure 1 could indeed possibly be considered for capacity calculations. However, in such a case power law curves corresponding to the AS 4672.1:2007 strength limits would need to be derived since the fpy\*/fpb ratio of AS 4672.1 differs slightly from that used by Mattock1. It should also be noted that AS 4672.1:2007 does not specify a limit for fpy\* (i.e. stress at 1% strain) but specifies the 0.1% and 0.2% proof strengths instead. The 0.2% proof strength can reasonably be taken as being equal to fpy\*. The effect of considering such a power law formulation rather than the proposed piece-wise linear curves in Figure 2 is considered in later sections of this paper.

Figure 2 Stress-strain curves proposed for 12.7mm, 15.2mm and 15.7mm strands

Figure 3 Distribution of failure strains (as per supplier provided LTQ test data - 527, 1135 and 157 tests for 12.7mm, 15.2mm and 15.7mm strands respectively)



Number of tests

Table 2 Statistics of failure strains as per supplier provided LTQ test data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Strand type | No of tests | Minimum εpb | Maximum εpb | Mean εpb | Standard deviation | 95% (upper) characteristic |
| 12.7mm | 527 | 0.045 | 0.084 | 0.064 | 0.0054 | 0.073 |
| 15.2mm | 1135 | 0.040 | 0.079 | 0.061 | 0.0029 | 0.066 |
| 15.7mm | 157 | 0.045 | 0.065 | 0.060 | 0.0030 | 0.065 |

Figure 4 Comparison of proposed stress-strain curves with supplier provided LTQ test data

1. 12.7mm strands
2. 15.2mm strands
3. 15.7mm strands

Table 3 Statistics of strength data as per supplier provided LTQ test data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Property | Strand nom. diam. mm | No. of test data | Ratio w.r.t limit in A4672.1:2007 | Ratio w.r.t experimental Fpb |
| Min | Mean | 5% lower charact. | Min | Mean | 5% lower charact. | AS 4672.1 limit |
| F0.1%  | 12.7 | 527 | 1.081 | 1.168 | 1.136 | 0.829 | 0.902 | 0.880 | 0.821 |
| 15.2 | 1135 | 1.116 | 1.165 | 1.138 | 0.872 | 0.907 | 0.893 | 0.820 |
| 15.7 | 157 | 1.064 | 1.092 | 1.071 | 0.880 | 0.904 | 0.888 | 0.860 |
| F0.2% | 12.7 | 335 | 1.108 | 1.147 | 1.125 | 0.895 | 0.916 | 0.899 | 0.848 |
|  | 15.2 | 373 | 1.102 | 1.138 | 1.122 | 0.906 | 0.921 | 0.911 | 0.851 |
|  | 15.7 | 61 | 1.050 | 1.073 | 1.051 | 0.905 | 0.919 | 0.907 | 0.892 |
| Fpb | 12.7 | 527 | 1.035 | 1.063 | 1.049 | N/A |
|  | 15.2 | 1135 | 1.025 | 1.053 | 1.039 |
|  | 15.7 | 157 | 1.020 | 1.040 | 1.028 |
|  | **Strand** | **No. of tests** | **Experimental values (GPa)** | **AS 4672.1 specified** |
| Min | Mean | 5% lower charact. |
| E | 12.7 | 527 | 190 | 200 | 194 | 195 +/- 10  |
| 15.2 | 1135 | 189 | 197 | 192 |
| 15.7 | 157 | 187 | 198 | 194 |

The impacts of using the proposed stress-strain curves viz. Equation 1 can be assessed by considering the respective flexural capacity predictions using the two methods. Five Teeroff beam sections, with section properties and material data as shown in Table 4, were used for this purpose. Teeroff beams are a popular form of beam construction in Western Australia where the shape is like that of a Super-T beam but with much wider flanges. The Teeroff beam section is shown qualitatively in Figure 5, along with the deck slab which acts compositely with the Teeroff beam. The sections listed in Table 4 are of actual beams that have been constructed in WA. While the actual sections used 15.2mm Grade 1830 MPa strands, purely for the purpose of assessing the performance of the proposed stress-strain curves for the two other strand types, all strands of the section(s) have been considered substituted with the respective strand type under consideration. Flexural capacities were calculated in line with Cl 8.1.2 of AS 5100.5:2017 with the effective prestress considered over the full composite section for simplicity.

Figure 5 Teeroff beam section used for flexural capacity calculations



Table 4 Properties of Teeroff beams considered for flexural capacity comparison (to be read with Figure 5, note It ≡ Transformed gross concrete second moment of area, At ≡ Transformed gross concrete area)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  SectionProperty  | Sect1 | Sect2 | Sect3 | Sect4 | Sect5 |
| dbeam mm | 650 | 1000 | 1300 | 1800 | 2200 |
| bef mm | 2790 | 2685 | 4968 | 4532 | 4956 |
| ddeck mm | 230 | 200 | 200 | 200 | 200 |
| bbf mm | 1400 | 1050 | 1400 | 1400 | 1500 |
| Strands in Layer1 | 24 | 14 | 22 | 18 | 20 |
| Strands in Layer 2 | 24 | 14 | 22 | 24 | 26 |
| Strands in Layer 3 | 0 | 14 | 20 | 24 | 26 |
| Strands in Layer 4 | 0 | 2 | 0 | 24 | 26 |
| Strands in Layer 5 | 0 | 0 | 0 | 6 | 6 |
| It m4 | 0.09593 | 0.1934 | 0.494 | 1.104 | 1.843 |
| At m2 | 1.16 | 1.117 | 1.827 | 2.000 | 2.215 |
| yt m | 0.344 | 0.453 | 0.489 | 0.737 | 0.891 |
| f’c\_deck MPa | 40, 50 |
| Ec of beam concrete GPa | 34.8 | 34.8 | 37.4 | 37.4 | 37.4 |
| ylayer1 mm | 75 | 60 | 60 | 60 | 60 |
| fpe | 0.525fpb, 0.45 fpb corresponding to 30% and 40% loss from an initial jacking stress of 0.75fpb respectively |

Table 5 Ratios of ULS flexural capacity predictions obtained using Equation 1 to those obtained using the proposed stress-strain curves (fpe1 = 0.525fpb, fpe2 = 0.45fpb)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Teeroff section |  Strandf’c\_deck MPa | 12.7mm | 12.7mm | 15.2mm | 15.2mm | 15.7mm | 15.7mm |
| fpe1 | fpe2 | fpe1 | fpe2 | fpe1 | fpe2 |
| 1 | 40 | 1.049 | 1.052 | 1.047 | 1.050 | 1.011 | 1.013 |
| 2 | 40 | 1.031 | 1.033 | 1.046 | 1.049 | 1.020 | 1.022 |
| 3 | 40 | \* | \* | 1.019 | 1.021 | 1.009 | 1.011 |
| 4 | 40 | 1.007 | 1.009 | 1.034 | 1.036 | 1.017 | 1.019 |
| 5 | 40 | \* | \* | 1.019 | 1.022 | 1.009 | 1.011 |
|  |  |  |  |  |  |  |  |
| 1 | 50 | 1.045 | 1.048 | 1.049 | 1.052 | 1.016 | 1.018 |
| 2 | 50 | 1.021 | 1.023 | 1.042 | 1.044 | 1.019 | 1.022 |
| 3 | 50 | \* | \* | 1.007 | 1.010 | 1.002 | 1.004 |
| 4 | 50 | 0.993 | 0.995 | 1.025 | 1.028 | 1.013 | 1.015 |
| 5 | 50 | \* | \* | 1.007 | 1.010 | 1.003 | 1.005 |

From the values in Table 5 it is evident that, in general, the flexural capacities predicted using the proposed stress-strain curves are conservative compared to those calculated using Equation 1 (i.e. corresponding to ratios > 1 in Table 5). This is so for all cases except for Section 4 for the scenario when 12.7mm strands are considered. The capacities calculated using the proposed stress-strain curves were observed to be up-to ~5% more conservative for the sections considered. However, the level of conservativeness was less for the three deeper sections (Section 3 to 5) that were considered compared to the two shallowest sections.

It should be noted that the comparison shown in Table 5, with all strands considered to be 12.7mm should be treated as indicative only. This is since the level of prestressing is inherently related to the section geometry (as well as the beam span) and as such, for a given section which in actuality requires 15.2mm strands, the same number of 12.7mm strands will not suffice. This is evident by the fact that for some sections (marked with an asterisk \* in Table 5) a solution could not be found where the maximum strain in the strands was less than the breaking strain (0.05) at the point of crushing of the extreme compressive fibre. The comparison in Table 5 with all strands substituted with 12.7mm strands was purely undertaken to compare the performance of the stress-strain curves viz. Equation 1. 12.7mm strands are not used for contemporary Teeroff beam designs in WA and their use tends to be limited to prestressed planks. As such, for the remainder of the paper 12.7mm strands will not be considered for calculating flexural capacity predictions.

On the other hand, the use of 15.7mm strands in substitution of the 15.2mm strands is reasonable as such a scenario provides more than the prestressing corresponding to the 15.2mm strands (and as such could result in a given section being able to span a larger span for example). For the sections considered, it was observed that, in general, the level of conservativeness of the proposed approach compared to Cl 8.1.7 of AS 5100.5:2017 (i.e. Equation 1), was reduced when all the strands were substituted with 15.7mm strands. This can be attributed to the fact that the fpy(=f0.1%)/fpb ratio for 15.7mm strands is 0.86 compared to 0.82 for 15.2mm strands in AS 4672.1 and as such, the stress-strain curve becomes closer to fpb at lower strains for the 15.7mm strands. The stress-strain curves used by Mattock1 when developing Equation 1 also considered an fpy\*/fpb ratio of 0.85 which agrees well with the AS 4672.1 limits for 15.7mm strands than for 15.2mm strands and as such results in the reduced conservativeness (i.e. better agreement) seen for the 15.7mm strand scenarios.

The effect of the initial level of prestress (fpe) was seen to be negligible. The level of conservativeness increased marginally (~0.3%) for the lower level of fpe that was considered. No significant difference in the level of conservativeness was seen for Sections 1 and 2 for the two f’c values that were considered. However, for the three deeper (and larger) sections, the level of conservativeness decreased for f’c equal to 50MPa compared to 40 MPa. In general, the reduced conservativeness (or in other words better agreement) between the proposed approach and that using Equation 1, was when the strain levels in the tendons were calculated to be closer to 5%. This was the case for the three deeper sections for f’c equal to 50 MPa as opposed to 40 MPa. It should be noted that for the sections considered, in reality, the deck f’c value was 40 MPa, which is typically the concrete grade used in WA for decks composite with Teeroff beams.

From Table 5, it can be ascertained that for some typical Teeroff section designs, flexural capacities up-to 5% less than those predicted through the use of Cl 8.1.7 of AS 5100.5:2017 may result through the use of the proposed stress-strain curves. However, the proposed approach provides a consistent and rational basis founded in the limits defined in AS 4672.1 which is the material specification that all prestressing steel used for bridge construction in WA (and Australia) conform to. It removes ambiguity in the code in relation to what form of stress-strain curve can be used for prestressing steel and errs on the side of conservativeness by adopting a piece-wise multi-linear approach. For relatively deeper sections, such as Sections 3 to 5 in Table 5, the level of conservativeness observed of this approach is minor. The conservativeness in the approach is directly related to the piece-wise linear approximation adopted. In reality, the stress-strain curve will be ‘rounded’ leading to greater stresses at lower strains compared to εpb. However, the adoption of a rounded form of curve depends on being able to be confident about the shape of the actual stress-strain curves. If extensive test data are available of such stress-strain curves, representative of the range of prestressing steels in the market, then an approach similar to that followed by Devalapura and Tadros5 can be followed to derive a less conservative stress-strain curve. Until such an exercise is done, the proposed approach is a reasonable compromise. The sensitivity of the flexural capacity to the use of a rounded stress-strain curve rather than a piecewise linear stress-strain curve is discussed in a later section of this paper.

## Comparison of proposed stress-strain curves with sample test data

Upon request, SANWA Pty Ltd (supplier) and Siam Industrial Wire (producer) provided Main Roads WA a sample of their long term quality testing (LTQ) strength test data for the three strands types shown in Figure 2. The test data included modulus of elasticity, 0.1% proof strength, 0.2% proof strength, breaking strength and failure strain. This test data is compared to the proposed stress-strain curves in Figures 3a, 3b and 3c with the corresponding statistics given in Table 3. It should be noted that the number of data available for 0.2% proof strengths was reduced as the 0.2% proof strength is not part of the typical LTQ test record.

It should be noted that the test data that was provided corresponded to tests carried out on steels of different batches. However, for the purposes of Table 3, all data for a particular strand type were treated as being of the same population.

It is evident from Figures 3a-c that the test data lie notably higher than the proposed curves. Even the piece-wise linear approximations constructed using the respective 5% characteristic values of the test data (with the 95% characteristic considered for the failure strain) lie above the proposed stress-strain curves. However, it should be noted that this comparison is for test data provided by one supplier and as such should not be taken to be the generalised case without investigating the corresponding test data. Nonetheless, it is certainly indicative of the conservativeness of the proposed stress-strain curves as well as the AS 4672.1:2007 limits. Even if the minimums of the respective test strengths were considered along with the maximum failure strain out of all the test data, the resulting piece-wise linear approximation lies largely above the proposed curves except for a small region near 5% strain. With respect to the modulus of elasticity, good agreement was observed between the 5% characteristic values and the value specified in AS 4672.1:2007.

From Table 3, it is also evident that the salient F0.1% and F0.2% values (5% characteristic as well as minimums) are much greater than the corresponding limiting values in AS 4672.1:2007. This is the case for all strand types but much more notably so for 12.7mm and 15.2mm strands. This indicates that reconsideration of the strength limits in AS 4672.1:2007 may be warranted. However, a caveat should be added that the values in Table 3 are based only one on set of test data from one supplier. Yet, it is indicative of the type of prestressing steel that is currently in the market. The 5% characteristic breaking strengths were also found to be greater than the minimums specified in AS 4672.1:2007 although by lesser margins than for the 0.1% and 0.2% proof strengths. Nonetheless, the test data indicates that a more extensive study to re-visit the AS 4672.1:2007 limits may be worthwhile especially since increased strength can lead to greater flexural capacity and associated economies for a given strand layout.

In relation to the ratios of F0.1% and F0.2% to Fpb, it can be seen from Table 3 that for 15.7mm strands (of Grade 1860 MPa) there is reasonable agreement between the respective 5% characteristic values and the AS 4672.1 limits. The corresponding characteristic ratio of F0.2%/Fpb is also in good agreement with the Fpy\*/Fpb ratio specified in ASTM A4166 for low relaxation strands (noting that F0.2% ~ Fpy\* where the latter is the strand force at 1% strain).

However, the 5% characteristic ratios of F0.1%/Fpb and F0.2%/Fpb for 12.7mm and 15.2mm strands are notably higher than the corresponding AS 4672.1:2007 ratios. In fact, the characteristic ratios are closer to the corresponding ratios observed for the 15.7mm strands as well as the ASTM A4166 specified value for low relaxation strands. As all the test data were from low relaxation strands, this provides evidence that the F0.1%/Fpb and F0.2%/Fpb ratios in AS 4672.1:2007 as well as the definition of yield strength in AS 5100.5:2017 (0.82fpb) may warrant reconsideration. The ratios in AS 4672.1:2007 maybe lower since it caters for stress-relieved normal relaxation (Relax1) strand in addition to low relaxation strands. However, all prestressing steel that are used for bridge construction at present are low relaxation (Relax 2) strands. In fact, normal relaxation strands are no longer addressed in ASTM A416 which explains its higher Fpy\*/Fpb ratio. Higher F0.1%/Fpb and F0.2%/Fpb ratios would result in greater flexural capacities compared to those corresponding to the proposed curves in Figure 2.

The flexural capacities calculated for the five Teeroff sections detailed in Table 4, using piece-wise linear stress-strain curves for the following two scenarios (shown in Figures 3a to 3c), are compared in Table 6 to the capacities obtained using the corresponding curves in Figure 2.

1. Piece wise linear stress-strain curve constructed from test data minimums along with the maximum recorded failure strain in the test data
2. Piece wise linear stress-strain curve constructed from 5% (lower) characteristic test data along with 95% (upper) characteristic failure strain

Table 6 Ratios of ULS flexural capacity predictions obtained using stress-strain curves constructed from sample test data to those obtained using the proposed stress-strain curves (fpe = 0.525fpb)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Test curve | Teeroff section |  Strandfpe | 15.2mm | 15.2mm | 15.7mm | 15.7mm |
| f’c\_deck 40 MPa  | f’c\_deck 50 MPa | f’c\_deck 40 MPa | f’c\_deck 50 MPa |
| a)Using test mins | 1 | 0.525fpb | 1.067 | 1.063 | 1.036 | 1.034 |
| 2 | 1.051 | 1.044 | 1.029 | 1.026 |
| 3 | 1.020 | 1.010 | 1.015 | 1.011 |
| 4 | 1.034 | 1.026 | 1.022 | 1.018 |
| 5 | 1.020 | 1.010 | 1.015 | 1.011 |
|  |  |  |  |  |  |  |
| b)Using test charact. | 1 | 0.525fpb | 1.086 | 1.082 | 1.037 | 1.036 |
| 2 | 1.071 | 1.065 | 1.031 | 1.029 |
| 3 | 1.042 | 1.033 | 1.019 | 1.015 |
| 4 | 1.056 | 1.048 | 1.025 | 1.021 |
| 5 | 1.043 | 1.034 | 1.019 | 1.015 |

As would be expected from the fact that the stress-strain curves constructed from the characteristic (and even the minimum) test data lie above the proposed curves (as seen in Figures 3a to 3c), the corresponding predicted flexural capacities (ratios which are shown in Table 6) are notably higher than those obtained based on the curves in Figure 2. This provides an indication of the possible enhancement of flexural capacity that may be possible if AS 4672.1:2007 limits are updated based on an extensive test program of the prestressing steel currently available in the market. The level of conservativeness of the capacities calculated using the proposed curves was seen to reduce for the higher concrete grade that was considered as well as when 15.7mm strands were considered. These observations are consistent with what was observed previously in Table 5 as well in relation to the effect of the concrete grade and strand type.

## Effect of using alternative forms for proposed stress-strain curves

The proposed curves in Figure 2 are the most conservative design stress-strain curves that can be constructed based on the AS 4672.1:2007 limits. However, it is accepted knowledge that the stress-strain behaviour of prestressing steels is rounded in nature and as such rounded curve formulations may provide better representation of the actual reality. To investigate the potential benefit such formulations may result in, two alternative formulations namely the well-known three-parameter Ramberg-Osgood curve and the Power law curve (as described in Devalapura and Tadros5) were considered for comparison with the proposed curves. For these alternative formulations, the same limits specified in AS 4672.1:2007 were considered.

To derive the parameters of the respective Ramberg Osgood curves, the curves were fitted to go through the points (ε0.1%, f0.1%) and (εpb, fpb) with an initial gradient equal to 195GPa.

For the Power law curve parameters, the procedure outlined in Devalapura and Tadros5 was followed with the stress at 1% strain approximated as being equal to f0.2% and fitting the curve to go through (ε0.1%, f0.1%).

The resulting stress-strain curves are plotted in Figure 6 with the corresponding equations/parameters noted in Table 7.

Figure 6 Alternative stress-strain curve formulations based on limits in AS 4672.1:2007

1. 15.2mm strands
2. 15.7mm strands

Table 7 Equations of alternative forms of stress-strain curves to those proposed in Figure 2

|  |  |
| --- | --- |
| Form of curve | Equation |
| Ramberg Osgood fit | $$ε\_{ps}= \frac{f\_{ps}}{E}+α\frac{f\_{ps}}{E}\left(\frac{f\_{ps}}{f\_{0.1\%}}\right)^{n-1}$$For 15.2mm strands α = 0.1303, n = 18.659, f0.1% = 1496.5 MPaFor 15.7mm strands α = 0.1219, n = 24.575, f0.1% = 1600.0 MPa |
| Power law fit | As per Equation 2.For 15.2mm strands A = 5048.6, B = 189951.4, C = 120.8, D = 6.0321For 15.7mm strands A = 3285.4, B = 191714.6, C = 113.0, D = 7.7691 |

For a given strain, it is noted that both the Ramberg-Osgood and Power law fits give greater stresses compared to the proposed curves, given their rounded nature. The Ramberg-Osgood and power law fits are comparable for 15.7mm strands though the former develops stresses faster for 15.2mm strands.

It can also be seen that compared to the sample test data for 0.1% and 0.2% proof strengths, even the alternative stress-strain curve formulations are conservative although much closer to the characteristic test data values than the proposed curves. However, it should be noted that this observation is based on the limited test data that has been considered in this paper. If supported by more extensive stress-strain test data representative of all prestressing steels available in the current Australian market, then this suggests that these alternative formulations could be used for design albeit constructed based on the current AS 4672.1:2007 limits.

Flexural capacities of the five Teeroff sections given in Table 4 were calculated based on these alternative stress-strain curves and compared to those predicted using the proposed curves (of Figure 2). The ratios of the respective capacity pairs are given in Table 8.

Table 8 Ratios of ULS flexural capacity predictions obtained using alternative forms of stress-strain curves to those obtained using the proposed stress-strain curves (fpe= 0.525fpb)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Alt. curve type | Teeroff section |  Strandfpe | 15.2mm | 15.2mm | 15.7mm | 15.7mm |
| f’c\_deck 40 MPa  | f’c\_deck 50 MPa | f’c\_deck 40 MPa | f’c\_deck 50 MPa |
| Ramberg Osgood | 1 | 0.525fpb | 1.042 | 1.044 | 1.024 | 1.027 |
| 2 | 1.044 | 1.042 | 1.029 | 1.029 |
| 3 | 1.028 | 1.020 | 1.022 | 1.016 |
| 4 | 1.037 | 1.032 | 1.027 | 1.025 |
| 5 | 1.028 | 1.020 | 1.022 | 1.017 |
|  |  |  |  |  |  |  |
| Power law | 1 | 0.525fpb | 1.029 | 1.028 | 1.031 | 1.030 |
| 2 | 1.024 | 1.021 | 1.026 | 1.024 |
| 3 | 1.012 | 1.008 | 1.015 | 1.011 |
| 4 | 1.018 | 1.014 | 1.020 | 1.017 |
| 5 | 1.012 | 1.008 | 1.015 | 1.011 |

It is clear from Table 8 that the use of the alternative forms results in greater capacities than those calculated using the curves of Figure 2. However, in general, for deeper and larger sections (represented by Sections 3 to 5 in Table 8), the benefit is less compared to the two shallower sections. This is because the level of maximum strand strain at ULS is greater for Sections 3 to 5, resulting in smaller differences in the stresses corresponding to the different stress-strain curves.

For 15.2mm strands, the Ramberg-Osgood formulation gave the greatest capacity (consistent with the comparison between the stress-strain curves in Figure 6) while for the 15.7mm strands this was dependant on the level of maximum strain at failure (again consistent with the behaviour shown in Figure 6b).

Given the relatively small benefit gained by using alternative ‘rounded’ formulations (~2-3% on average for the scenarios considered in Table 8) and the fact that no certainty exists as to the statistics of the ‘shape’ of actual stress-strain curves from test data (as that would require an extensive study of all prestressing steels available in the market), use of the proposed curves in Figure 2 for design is reasonable. However, the potential capacity benefit on offer does support future testing work to establish a database of stress-strain curves to develop a ‘rounded’ design stress-strain curve representing such test data. A method like that followed by Devalapura and Tadros5 in developing their proposed design stress-strain curve can be utilised in this regard. It should be noted that the existing Cl 8.1.7 of AS 5100.5:2017 (which specifies Equation 1) was also developed based on work carried out using a power-law stress-strain curve.

## Sensitivity of proposed curves and corresponding capacities to the assumed failure strain

As noted previously, the proposed stress-strain curves in Figure 2, assume a failure strain (εpb) equal to 5%. The reasons for this have been discussed in earlier sections of this paper. However, as observed in Table 2, the 95% characteristic values of εpb calculated from sample test data are notably higher (~ 6-6.5%). As such, the effect of using a failure strain different to 5% for the curves proposed in Figure 2 has been considered in this section. Two alternative failure strains, namely 3.5%, which is the minimum value specified in AS 4672.1:2007 and 6.5%, representative of the characteristic values of the test data were considered for this exercise. The resulting stress-strain curves are shown in Figure 7. Flexural capacities calculated using curves based on these two alternative failure strains to those calculated using the proposed curves of Figure 2 are compared in Table 9.

Figure 7 Effect of alternative εpb values on proposed stress-strain curves

1. 15.2mm strands
2. 15.7mm strands

Table 9 Ratios of ULS flexural capacity predictions from stress-strain curves constructed based on εpb values equal to 3.5% and 6.5% to those obtained using the proposed stress-strain curves in Figure 2 (fpe= 0.525fpb)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| εpb | Teeroff section |  Strandfpe | 15.2mm | 15.2mm | 15.7mm | 15.7mm |
| f’c\_deck 40 MPa  | f’c\_deck 50 MPa | f’c\_deck 40 MPa | f’c\_deck 50 MPa |
| 3.5% | 1 | 0.525fpb | 1.017 | 1.021 | 1.010 | 1.013 |
| 2 | 1.030 | 1.035 | 1.019 | 1.023 |
| 3 | \* | \* | 1.035 | \* |
| 4 | 1.041 | 1.047 | 1.028 | 1.032 |
| 5 | \* | \* | 1.035 | \* |
|  |  |  |  |  |  |  |
| 6.5% | 1 | 0.525fpb | 0.992 | 0.990 | 0.996 | 0.994 |
| 2 | 0.986 | 0.983 | 0.991 | 0.989 |
| 3 | 0.975 | 0.972 | 0.983 | 0.981 |
| 4 | 0.980 | 0.977 | 0.987 | 0.985 |
| 5 | 0.975 | 0.972 | 0.983 | 0.981 |

As expected, the use of a smaller failure strain (i.e. 3.5%) results in greater capacities compared to those using 5%. It is noted that the difference in capacities between the scenarios using 3.5% failure strain vs those using 5%, is, in general, greater than the difference between the capacities corresponding to 6.5% vs 5%. For the scenarios considered in Table 8, the difference between the capacities corresponding to 6.5% and 5% failure strains was on average ~ 1.6% vs ~ 2.7% between the capacities obtained using εpb equal to 3.5% and 5%. In other words, the flexural capacities were observed to be less sensitive to increasing εpb (from 5%) than decreasing εpb.

The capacity benefit of using the lower εpb that was considered was greater for the three deepest sections compared to the two shallower sections.

It should be noted that even though AS 4672.1:2007 specifies a minimum εpb value of 3.5%, adopting this limit for the design stress-strain curve can result in solutions corresponding to concrete crushing at ULS not being possible (since strain demand in tendons is greater than εpb). This was the case for several scenarios in Table 8 which are indicated by an asterisk (\*). In practice, designers circumvent this limitation by considering a stress plateau equal to fpb for strains greater than 3.5%. However, this then is not consistent with the assumption of a ‘failure strain’. Adopting the 3.5% as the failure strain, also results in the most beneficial piece-wise linear stress-strain curve that can be constructed using the AS 4672.1:2007 limits. For these reasons, it is felt that not adopting the minimum εpb specified in AS 4672.1:2007 for the proposed curves of Figure 2 is appropriate.

Given the relatively minor difference in capacity between scenarios using failure strains of 5% and 6.5%, and given the inherent conservativeness associated already with the proposed stress-strain curves (i.e. compared with test data as well as due to the piece-wise linear formulation adopted), the comparisons in Table 9 would appear to support the adoption of 5% as the failure strain for the proposed stress-strain curves for design.

## Comparison of proposed stress-strain curves with those found in the literature

Even though AS 5100.5:2017 does not specify a stress-strain curve for prestressing strands, several design stress-strain formulations for strands were found in the published literature. These are tabulated in Table 10. Out of the three strand grades considered in this paper (i.e. 1870 MPa for 12.7mm, 1830 MPa for 15.2mm and 1860 MPa for 15.7mm), comparable stress-strain curves could only be found in the literature for the Grade 1860 MPa (270 ksi) strands. As such, a comparison with the formulations found in the literature is only possible for the proposed stress-strain curve for Grade 1860 MPa 15.7mm strands. This comparison is shown in Figure 8.

Table 10 Stress-strain formulations found in the published literature

|  |  |
| --- | --- |
| Source | Stress-strain curve (fps in MPa) |
| Commentary on CSA S6:197  | $f\_{ps=}Eε\_{ps} for ε\_{ps}\leq 0.008$ with E = 195 GPa$$f\_{ps}=1848- \frac{0.517}{ε\_{ps}-0.0065}\leq 0.98f\_{pb} for ε\_{ps}>0.008 $$ |
| PCI Bridge Design Manual8 | $f\_{ps=}198569 ε\_{ps} for ε\_{ps}\leq 0.0085$ $$f\_{ps}=6.89476\left(270- \frac{0.04}{ε\_{ps}-0.007}\right) for ε\_{ps}>0.0085 $$ |
| Devalapura and Tadros5 | As per Equation 2 with A = 6115.7, B = 190385.0, C = 112.4, D = 7.36 but with fps subjected to a max limit of fpb |
| Eurocode 29 | Bi linear curve with fps = 195,000 εps for fps ≤ f0.1k$f\_{ps}= f\_{0.1k}+ \frac{f\_{pb}-f\_{0.1k}}{ε\_{pb}-ε\_{0.1k}}\left(ε\_{ps}-ε\_{0.1k}\right)$ Where ε0.1k = 0.001 + f0.1k / 195000, εpb = 0.02/0.9, f0.1k = 0.9fpb |

Figure 8 Comparison of stress-strain curves found in the published literature with that proposed for Grade 1860 MPa 15.7mm strands in Figure 2

1. Comparison with proposed curve in Figure 2 and alternative forms considered in Figure 6b
2. Comparison with proposed curve along with sample test data provided by a prestressing supplier at strains close to the 0.1% and 0.2% proof strengths

As is clear from Figure 8a, all four stress-strain curves considered in Table 10 develop stresses with strain more rapidly after the initial proportional region compared to the proposed curve for 15.7mm strands. This is most notably so for the PCI8 curve which shows the most ‘rounded’ behaviour. The four respective stress-strain curves can be seen to develop greater stresses at strains after 0.01 even compared to the alternative Ramberg-Osgood and power law fits to the AS 4672.1:2007 limits. However, the stress-strain curve of the Commentary on CSA S6-197 dips below the proposed curve for larger strains close to εpb as it has a maximum upper limit of 0.98fpb for the strand stress.

It is noted that the Eurocode 29 curve defines εpb to be equal to 0.022. As such, it can be expected that this particular curve will be of limited use since, as seen from previous sections, the strain demand in the strands at the ULS flexural capacity corresponding to concrete crushing is typically greater than this except for relatively smaller cross sections.

Comparing the afore-mentioned four stress-strain curves to the sample test data that was provided by a prestressing supplier (Figure 8b), it can be seen that the PCI8 stress-strain curve appears to be un-conservative compared to the 5% characteristic proof test data, indicating that for prestressing steels available in Australia it is unsuitable to be used for design. However, the other three curves lie below the characteristic values with the CSA7 curve providing the closest agreement to the 0.1% and 0.2% characteristic proof strengths. The Devalapura and Tadros5 curve also compares well with the characteristic proof strengths. This curve was derived based on the 1% characteristic fit to data obtained from a series of tests carried out on Grade 1860 MPa strands. It develops stresses equal to fpb at relatively smaller strains (~0.028) given that it is a fit to actual test data (rather than compliance minimums). This is consistent with the observed behaviour in the sample test data considered in this paper where the test strengths were observed to be notably higher than the compliance minimums. The Devalapura and Tadros5 curve has a maximum stress cutoff of fpb (i.e. the minimum breaking strength as per the specification) and as such the curve contains a stress plateau equal to fpb. This suggests that, if significant test data of prestressing steels used in Australia are obtained, then a design stress-strain curve, more representative of actual strand behaviour, can be derived following a similar method to that followed by Devalapura and Tadros5.

The flexural capacities of the five Teeroff sections given in Table 4, calculated following the four stress-strain curves given in Table 10, are compared to those calculated using the proposed curve for 15.7mm strands (in Figure 2) in Table 11.

For the Eurocode 2 stress-strain curve, for all sections except the shallowest section (Section 1) solutions could not be found which gave strand strains less then εpb for a strain profile corresponding to concrete crushing. This is indicated by asterisks (\*) in Table 11. As discussed previously, this is a consequence of the low εpb value recommended in Eurocode 2. For sections for which the strain demand at ULS is greater than this recommended value, Eurocode 2 specifies using a elastic-plastic approximation using 0.9fpb as the yield stress.

For the other three stress-strain curves, it can be seen from Table 11 that notably greater flexural capacities were obtained compared to those obtained from the proposed curve. The capacities were also observed to be greater than those predicted by the alternative curve fits to AS 4672.1:2007 shown in Figure 6, though for the CSA S6-197 curve this was the case only for the two shallower sections. This is consistent with the greater development of stress with strain of the four curves given in Table 10, compared to those in Figure 2 and Figure 6.

On average, the PCI8 curve gave the highest capacities for all the sections considered. This was markedly so for the two shallower sections that were considered. This is consistent with the relatively low ULS strain demand of those two sections and the fact that the PCI8 curve has greater stresses at lower strains. However, as noted previously, the PCI8 predictions could be potentially unconservative compared to the test data since as can be seen in Figure 8a, it lies above the characteristic proof strengths calculated from the test data.

The Devalapura and Tadros5 curve predictions were also notably greater than the predictions calculated using the proposed curve (i.e. on average ~ 5% higher). For the three deeper sections that were considered (Sections 3 to 5) it gave the highest capacities out of the four curves which is consistent with the fact that it achieves an fpb plateau at a relatively low strain. Given that this curve is based on a 1% characteristic fit to actual test data, this provides an indication of the potential benefit, in relation to flexural capacity, of developing a stress-strain curve founded in actual test data rather than compliance minimums. The benefit will further increase if the stress was not capped to be the minimum fpb corresponding to the nominal grade of the strand.

The ratios of the CSA S6-197 curve capacities to those of the proposed curve decreased for the larger sections compared to the two smaller sections which is in line with expectation as the maximum strand stress is capped at 0.98fpb in that particular curve and as such, there is reduced stress difference between the CSA curve and the proposed curve for larger strains (and since the strain demand for the larger sections at ULS is higher).

Table 11 Ratios of ULS flexural capacity predictions obtained using four stress-strain curves found in the literature to those obtained using the proposed stress-strain curve in Figure 2 for Grade 1860 MPa 15.7mm strands (fpe= 0.525fpb)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| f’c\_deck MPa | Teeroff section |  Curvefpe | CSA7 | PCI8 | Devalapura and Tadros5 | Eurocode 29 |
| 40 | 1 | 0.525fpb  | 1.054 | 1.074 | 1.051 | 1.045 |
| 2 | 1.050 | 1.065 | 1.056 | \* |
| 3 | 1.023 | 1.038 | 1.044 | \* |
| 4 | 1.038 | 1.052 | 1.058 | \* |
| 5 | 1.023 | 1.038 | 1.044 | \* |

# Conclusion

Based on the discussions of the foregoing sections, the following conclusions can be arrived upon.

* The multi-linear design stress-strain curves proposed for 12.7mm, 15.2mm and 15.7mm strands in the Main Roads WA Bridge Branch design information manual provide a consistent, rational and conservative basis for capacity calculations, founded in the material specification for prestressing strands, i.e. AS 4672.1:2007. This provides industry-wide uniformity for the design process, provides the explicit ability to compare the strand strain demand at ULS against the breaking strain, and is applicable for any strand layout with any effective prestress, unlike the current conditional guidance in AS 5100.5:2017.
* The flexural capacities calculated using the Main Roads WA proposed curves are more conservative than those obtained following Cl 8.1.7 of AS 5100.5:2017 by up-to ~5% and ~2% on average, based on a selection of as-constructed Teeroff sections of existing bridges in WA. This level of conservativeness, which reduces notably for deeper and larger sections, is not felt to be prohibitive to the adoption of the proposed curves, given the resulting benefits.
* The proposed curves are based on an assumed a failure strain of 0.05. This is consistent with precedents in the literature and even though the 95% characteristic failure strains obtained from sample test data tended to ~ 6 - 6.5%, a value of 5% is acceptable as the corresponding increase in capacity compared to 6.5% is minor and given the inherent conservativeness of adopting a multi-linear approach to the curves.
* Fits of more ‘rounded’ stress-strain formulations to the AS 4672.1:2007 limits provide greater flexural capacities than those obtained using the proposed curves. However, the adoption of such forms needs to be supported by extensive test data of the full range of prestressing steels currently in the Australian market. In the absence of such work, the proposed multi-linear form provides an acceptable consistent approach.
* Characteristic proof and breaking strengths corresponding to a sample of long-term quality test data made available from a supplier suggest that for prestressing steels currently in the Australian market, the specified compliance minimums in AS 4672.1:2007 may be too low and warrant reconsideration. This is both in relation to the absolute values as well as in relation to the ratios of proof strengths to breaking strength. It appears reasonable to have separate compliance minimums for low relaxation strands rather than to cover all stress-relieved strands (normal and low relaxation) in one standard. Reconsideration of the above values and ratios will result in more favourable multi-linear stress-strain curves resulting in greater flexural capacities.
* It is recommended that consideration be given to leveraging test data to reliably obtain a characteristic stress-strain curve representative of all prestressing steels available in the market in Australia. Precedents that exist in the literature for such efforts indicate that notable benefit (~5% for typical Teeroff beam sections), in relation to flexural capacity, can result from a test-based design stress-strain curve obtained in this manner. Records of long-term quality testing data of prestressing steels can be utilised for this purpose and it is hoped that strand suppliers can make such data widely available to clients and designers to facilitate that effort.

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