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Discussion: Pull-out and push-in tests of bonded steel strands

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An interesting study on strands for structural strengthening use is presented by Faria *et al.* (2011a). However, some questions should be clarified on the local bond–slip relationship.

In relation to Figure 27, the authors propose Equation 2, including $C = 13{\cdot}4$ and $b = 0{\cdot}175$ for strands (15·2 mm), and factors of 1·25 and 0·75 to obtain the upper and lower bounds, respectively. Equation 2a in their paper is equation 7 in Balázs (1992), with $C = 13$ and $b = 0{\cdot}25$ for strands (12·8 mm). Moreover in Balázs (1992), the bond stresses were related to concrete strength (equation 9a), and factors of 1·35 and 0·65 for bounds of bond stresses were proposed (equation 9b) resulting in transmission length (L_t) bound values of $0{\cdot}79L_t$ and $1{\cdot}41L_t$ (see other L_t bound values in Martí-Vargas *et al.* (2007a)). This raises the following questions.

(*a*) Does it mean that C is independent of strand diameter?
(*b*) What concrete strength was used?
(*c*) Why use factors 1·25 and 0·75? It seems that the upper bound can be reduced.
(*d*) Could the authors provide bound values of L_t?

In relation to the theoretical procedure by Balázs, it appears that only Equation 3 was given by Balázs. However, it should be clarified that most of the equations were given by Balázs (1992): Equation 4 is equation 10 in Balázs (1992), Equation 5 is equation 12, Equation 7 is equation 13, and Equation 9 is equation 17. The authors' contribution is λ, which is not suitable to obtain L_t. Moreover, it seems that some errata/mistakes and the subsequent comparisons should be clarified and revised.

(*a*) The ratio nominal/actual strand area is missing in the A parameter, Equations 7 and 9.
(*b*) In A, the $\pm$ symbol.
(*c*) In λ, simplify $[2/(1-b)]$ and $[(1-b)/2]$.
(*d*) Exponents: $[2b/(1-b)]$ in Equation 5; $[(1-b)/(1+b)]$ in Equation 9.
(*e*) Equations 7 and 9: A^b instead of A.
(*f*) Equation 9: $\sigma_s(\xi = 0)$ instead of σ_s.
(*g*) Equation 10: $s(\xi = l_t/\mathrm{d})$ instead of $\delta(\xi = l_t)$.

In relation to the state of the art, relevant/complete/recent references such as Martí-Vargas *et al.* (2007b) have not been considered in this paper. In spite of this fact, it seems there are some coincidences between them.

(*a*) Conclusion 5 from Martí-Vargas *et al.* (2007b) coincides with an idea of a 'false perception determining transmission length', which appears in the main text, as a conclusion and in the abstract. This coincidence enhances the validity of the conclusion on a subject with no consensus (Palmer and Schultz, 2011, 2012).
(*b*) A particular manner of adding the strand stress characterisation to define α values is used in both works.
(*c*) Based on the results using the ECADA test method (Martí-Vargas *et al.*, 2006), $\alpha = 2{\cdot}44$ for Guyon's expression (Guyon, 1953) is proposed in Martí-Vargas *et al.* (2007b) for strands of 12·7 mm. Moreover, $\alpha = 2{\cdot}44$ appears directly in Figure 32, but it has not been mentioned/substantiated in the related text. On the other hand, as $\alpha = 2/(1-b)$ (Balázs, 1993), if $b = 0{\cdot}175$ then $\alpha = 2{\cdot}42$ (strands 15·2 mm) and not 2·44, then $b = 0{\cdot}18$. Does this coincidence mean that b is independent of strand diameter?

Authors' reply

The authors would like to thank the contributor for his interest in their work. All his questions are answered and discussed below, and the opportunity has been taken to clarify some issues.

The authors' work focuses on the study of the bond behaviour of prestress steel strands bonded with an epoxy-based bonding agent in holes previously drilled in hardened concrete, to be used in a strengthening technique (Faria *et al.*, 2011b, 2012a, 2012b). This is distinct from the traditional pretensioning technique where prestress steel strands are embedded in concrete, about which a lot of information and references relative to a number of research works can be found (see *fib Bulletin 10*; fib, 2000), including those by Balázs (Balázs, 1992, 1993).

The authors decided to approach the problem from a general angle by adopting a non-linear bond stress–slip law (Equation 2a) similar to equation 19 in (Balázs, 1987), instead of using equation (6.3.1) in *fib Bulletin 10* (fib, 2000), which corresponds to equation 9a in Balázs (1992), since this last was proposed as assuming a certain relation with the square root of the concrete compressive strength. Also, the use of a general approach appears to be more reasonable (Equation 2a) since, as with reinforcement steel bars, prestress strand bond behaviour is influenced by factors such as the concrete mechanical properties and its constitution, its positioning, the shape of the outer surface, the pitch of the strand external wires, pull-out or push-in situations, and so on (see, for example, Balázs (1987, 1992, 2007), Carmo (1999), *CEB Bulletin 181* (CEB, 1987), *CEB Bulletin 212* (CEB, 1992), *fib Bulletin 10* (fib, 2000) and Lopes and Carmo (2002)). In the present authors' case, important additional parameters also play a role in bond behaviour, especially the bonding agent used and the construction procedures associated with drilling and cleaning the holes, and so on (see, for example, Cook *et al.* (1998), Cook and Konz (2001), Laldji (1987), Laldji and Young (1988), Walther and Soretz (1967) and Zamora *et al.* (2003)). The bonding agent used has been found to provide good bonding properties in post-installed ordinary reinforcement bars (HILTI, 2005) when compared with traditional concrete-embedded reinforcement bars, and the same is expected to happen with prestress steel strands when similar construction procedures are adopted. Taking all the above into account, the following points can be made.

- Parameters C and b in Equation 2a were determined experimentally, as explained in the original paper, and more experimental tests are needed to determine what their relations with the several factors mentioned above are, in particular with the strand diameter, as queried by the contributor; so, in the authors' opinion, it is not correct to relate the value of C proposed by the authors directly with that determined or computed as proposed by Balázs (1992), since in the present authors' case the concrete compressive strength is not the governing parameter, because the bond depends mainly on the bonding agent used. Moreover, for a 12·8 mm nominal diameter strand embedded in a concrete with a 25·7 MPa compressive strength (compressive strength of pull-out test specimens used in the original paper), using equation 9a in Balázs (1992), a value of C = 10·4 MPa results, which is somewhat lower than C = 13·0 MPa, determined by Balázs (1992) when testing in a 40 MPa compressive strength concrete. The non-linear law presented in the original paper (Equation 2a) is valid up to a slip of 5 mm, corresponding to a maximum bond stress of 11 MPa, while Balázs's law (Balázs, 1992) is valid up to a slip of approximately 1·5 mm, leading to a maximum bond stress of 6·1 MPa.
- The results and their theoretical interpretation are valid for the test conditions and material mechanical properties, including the concrete compressive strength, presented in the paper (see the section of the paper entitled 'Experimental research'), although this characteristic is not relevant in the present authors' case.
- In fact, in Figure 27 it is only possible to see an upper bound of approximately 10%. However, that figure does not include specimen PO-H5-100, whose maximum load (93·59 kN, see Table 3) was larger than the maximum loads for the other specimens with the same embedment depth, and whose behaviour could not be recorded for the reasons specified in the text. Taking into account the maximum load of PO-H5-100, its associated bond stress–slip law is expected to be above all others represented in Figure 27. So the authors assumed a scatter of ±25% for reasons of simplicity and uniformity. Moreover, Figures 28 and 29 indicate that it is possible to conclude that the adopted scatter is adequate (see text under Figure 29 on page 702 of the paper).
- Figures 28 and 29 can be used to see the bound values for the maximum and transmittable loads, or to determine the bound values of maximum embedment and transmission lengths, respectively, for the pull-out and push-in situations. Bound values for l_t may be computed using Equation 9.

As mentioned before, the authors adopted a general approach to interpreting the bond behaviour, through the use of Equation 2a. The theoretical analysis presented in their paper is based on Balázs's work (Balázs, 1987) (see page 701 of the paper under discussion), which sets out the detailed formulation and solution of the governing equation of the bond (Equation 3) when a non-linear bond stress–slip law such as Equation 2a is adopted, which applies to both pull-out and push-in behaviour, thereby covering the case studies used. In Balázs (1987), solutions are provided for the slip, bond stress and steel stress distribution along a bonded length for a generic situation using Equation 2a as an input. This generic situation may be a pull-out or a push-in situation, as long as the coordinates used have their origin at the point where the slip and the bond stress just appear (see figure 2 in Balázs (1987)) and that is what has been done in the present authors' work (see page 701). So, in the paper under discussion Equations 4, 5, 6 and 8 are similar to equations 48, 49, 50 and 51 in Balázs's work (Balázs, 1987), while Equations 7 and 9 are similar to equations 6 and 8, taking into account the changes in the coordinates' origin, as mentioned before. Since the nominal contact diameter/perimeter of the strand does not coincide with the strand diameter/perimeter equivalent to its real cross-sectional area (figure 5 and equation 20 in Balázs (1987)), the parameter Θ has to be introduced, which may be easily deduced using the procedure described in sections 2.3, 2.5, 3.1 and 3.2 of Balázs (1987). The present authors disagree with the contributor when he says that the authors have introduced the term λ. This term is introduced in Balázs (1987) and its purpose is to consider pull-out situations when the unloaded side slip is not zero, $\delta(\xi = 0) \neq 0$, which is appropriate for the case being discussed. The ± sign introduced by Balázs (1987) in A is also correct (it should also be in K), where the − sign stands for tensioned concrete and the + sign stands for compressed concrete, allowing the adoption of the procedure for both the pull-out and push-in situations, respectively. The subsequent work by Balázs (1992) applied the procedure previously mentioned in Balázs (1987), focusing only on the transmission case. Moreover, Balázs's work (Balázs, 1992) was concerned with concrete-embedded steel strands, assuming that the bond stress is proportional to the square root of the concrete compressive strength, and this relation is included in the equations presented for slip, bond stress and steel stress distribution along with the transmission length, which is not the present authors' case. In light of this, in the authors' opinion it makes sense to refer only to Balázs (1987). The authors appreciate the contributor calling their attention to typographical errors in some equations: the introduction of Θ in the A equation inside the brackets and as a multiplier of C in Equations 6–9; inclusion of A^b in Equations 6–9; exponent $[2b/(1-b)]$ in Equation 5; $[(1-\mathrm{b})/(1+\mathrm{b})]$ in the outermost exponent of Equation 8 and in Equation 9; $\sigma_s(\xi = 0)$ instead of σ_s in Equation 9; and $s(\xi = l_t/d)$ instead of $\delta(\xi = l_t)$ in Equation 10. Despite these typing errors, the correct equations were used in all the computations, results and conclusions presented in the paper.

The authors do not understand the contributor's objection regarding the definition of α, since they are using words similar to those that can be found in other works (see, for example, Balázs (1993), Carmo (1999), den Uijl (1998), *fib Bulletin 10* (fib, 2000) and Lopes and Carmo (2002)). For example, Balázs (1993) states the following: 'The α coefficient takes into account the assumed shape of the bond stress distribution', mentioning that $\alpha = 2$ in the case of constant bond stress distribution, being both the strand and concrete linear strains, and that $\alpha = 3$ in the case of linear bond stress distribution, where both the strand and concrete strains are parabolic; in *fib Bulletin 10* (fib, 2000) the following is found: 'α shape factor for steel stress distribution, which is connected to the bond stress distribution: a linear ascending, uniform and linear descending bond stress yield for α the values 1·5, 2·0 and 3·0, respectively'. Some of those works also mention that this coefficient may vary considerably, meaning that the determination of the transmission length of bonded strands in precast concrete may not be accurate when using draw-in values, that is intuitively, it is the same as saying that it leads to the erroneous conclusion that the transmission length varies considerably, as was mentioned in Martí-Vargas *et al.* (2007b). In the present authors' work this same conclusion was reached based on the experimental test results, for that specific situation (bonded strands using an epoxy adhesive). In the authors' opinion, this is one of the main reasons that has led to the development of a number of research works in the past 50 years, based on which different values for α have been proposed ($1{\cdot}5 \leqslant \alpha \leqslant 4$), as can be concluded, for example, from looking at Table 1 in Martí-Vargas *et al.* (2007b). The α coefficient in Equation 10, presented in Figure 32, was computed using the equations presented in the present authors' paper based on the work of Balázs (1987). In the text (page 702) the authors mention that they compare the computed and experimental strand draw-in results, and 'Theoretical results' is written in the key to Figure 32 for the solid line. The solid line in Figure 32 may be drawn using Equation 9 for several steel stresses ($\sigma_s(\xi = 0)$), along with the corresponding strand draw-in through the application of Equation 4. The difference between considering $b = 0{\cdot}175$ (see Equation 2a) or its rounded value of $b = 0{\cdot}18$ when computing the α coefficient ($\alpha = 2{\cdot}424$ and $\alpha = 2{\cdot}439$ for $b = 0{\cdot}175$ and $b = 0{\cdot}18$, respectively) is not significant, since it is approximately 0·6%.

In the authors' opinion, a direct relation between both cases, as queried by the contributor, cannot be drawn because

- The theoretical value of $\alpha = 2{\cdot}44$ was obtained in the original paper for a bonded steel strands situation, which is quite a different situation from that for which the experimentally determined value was found by Martí-Vargas *et al.* (2007b) and other previous work, which reports $2{\cdot}3 \leqslant \alpha \leqslant 2{\cdot}6$ (den Uijl, 1998).
- Martí-Vargas *et al.* (2007b) obtained their figure through a regression analysis of their experimental results, while in the discussed paper the figure was derived theoretically, as explained before.
- Furthermore, the authors recall that, as mentioned in the paper, a regression analysis of the experimental results returned an average of $\alpha \approx 1{\cdot}9$, with a relatively high degree of scatter, which differs from the theoretical computed value of 2·44.

With respect to the presentation of the results, authors of previous works, Balázs (1993), Carmo (1999) and Lopes and Carmo (2002) also chose to present their experimental results in a graph format that relates transmission length to strand draw-in, with the inclusion of lines corresponding to $\alpha = 3{\cdot}0$ and $\alpha = 2{\cdot}0$ or $\alpha = 1{\cdot}5$.

The question about the dependence of coefficients b in Equation 2a on several factors has been addressed earlier in this discussion. The authors also consider this a controversial question: Balázs (1987) experimentally determined similar values of b for deformed steel bars of varying diameters (0·4, 0·4 and 0·45 for deformed steel bars with diameters of 8 mm, 16 mm and 28 mm, respectively); with respect to concrete-embedded steel strands, Balázs (1992) determined a value of $b = 0{\cdot}25$ for strands with a nominal diameter of 12·8 mm, whereas Martí-Vargas *et al.* (2007b) found an average value ($\alpha = 2{\cdot}44$), theoretically equivalent to $b = 0{\cdot}18$ for strands with a similar nominal diameter (12·7 mm). This clearly shows that, in addition to the diameter, the several factors mentioned above in the text have an influence on both C and b, in Equation 2a.

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