Article

Assessment of Existing Bond Models for Externally Bonded SRP Composites

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Featured Application: The results presented in the manuscript may be helpful for designers in choosing the most appropriate bond model for SRP composites.

Abstract: This manuscript assessed the applicability of the existing ultimate bond formulas originally developed for externally bonded carbon fiber-based composites in the analysis of steel-reinforced polymers (SRPs). In the first part, the methods of predicting the bond capacity are reviewed, the differences are indicated, and the factors determining the bond are discussed; then, using the bond test results of over 400 samples available in the literature, the bond prediction methods are assessed by graphical comparison. The evaluation mainly concerned concrete elements and epoxy adhesives; however, to a lesser extent, a similar analysis was performed for the masonry substrate and grout matrices. The results showed the relatively good applicability of the majority of bond prediction models for the analysis of SRP composites. In most cases, the ultimate bond force was slightly underestimated, which was beneficial in the design of this type of strengthening. Larger discrepancies concerned weaker grout matrices.

Keywords: steel-reinforced polymers; strengthening of concrete; bond force

1. Introduction

Strengthening of structures with externally bonded reinforcement is nowadays the most popular method of restoring or improving the bearing capacity. The most popular in the construction industry are organic fibers, especially glass and carbon. For this reason, most of the standards and design methods have been developed based on research on these types of composites. This is a barrier to popularizing alternative, often equally effective and cheaper solutions [1]. An example is ultra-high tensile steel (UHTS) and textile composites that use it. They were placed on the market in 2004. Most of the first applications of these composites, mainly in the USA and Italy, are related to the work of research teams developed in these two countries [2–5]. Their research allowed for the dissemination of engineering knowledge necessary for the practical applications of steel-reinforced composites [6].

A modern structural engineer expects clear guidelines, manuals, and design standards. Such international and local documents can be found for carbon fiber reinforced polymer (CFRP) composites. This paper aims to answer, at least partially, the question of whether they can be used in the design of steel-reinforced polymer (SRP) strengthening. The comparison of the mechanical properties showed many similarities. Due to the high carbon content and drawing down to diameters of 0.20–0.35 mm, the tensile strength of pure steel cord is around 3000 MPa. Additionally, the modulus of elasticity is comparable (around 180–210 GPa). The differences appear in the fabrication method. CFRP composites can be made as strips, by a pultrusion process, and then adhered to the substrates, or as textiles. SRP composites are always textiles that are fixed in a wet lay-up process. Fiber volume fraction in the pre-cured laminate is significantly greater; therefore, CFRP strips maintain the properties

of the fibers. The strength and stiffness of the SRP related to the cross-section of the finished laminate can drop by more than three times [7], depending on the density of the cord and the amount of resin used. Both compared materials retain almost constant stiffness throughout the load range, although in the case of SRP composites, a short inelastic branch can be seen [8]; therefore, their fracture strain is about 50% greater [7].

The question is, how described differences affect the behavior of strengthened specimens. The analysis provided by Papakonstatntinou et al. [9] proved that in the case of flexural behavior, existing codes could be successfully used; however, in the case of SRP composites, the safety margin was significantly lower. It should be noted here that a structural element strengthened with an externally bonded composite usually exhibits forms of failure unknown for normal reinforced concrete. It could be a fracture of the fibers, or more commonly, debonding of the composite. Mitolidis et al. [8] showed clear differences in the bond strength and debonding slip. Proper modeling of debonding seems to be a key to the correct design of SRP strengthening. This manuscript assessed the existing strength anchorage models by testing them on a wide range of laboratory test results. The conclusions can be used in practice to select the safest and most accurate method of predicting the bond of SRP overlays.

2. Bond Performance of External Strengthening

Debonding can be defined as a brittle loss of adhesion between composite overlay and substrate. This is the most common failure mode of externally bonded fiber-reinforced strengthening systems. Existing design guidelines distinguish between four models of debonding. Originally, they were defined by Teng et al. [10]. Those are plate end interfacial debonding, concrete cover separation, intermediate flexural crack-induced debonding, and critical diagonal shear crack-induced debonding. Schematically they are presented in Figure 1. In the case of SRP composites, what can also occur is interlaminar failure at the matrix–fiber interface [11].

Figure 1. Debonding failure modes: (a) plate end interfacial debonding; (b) concrete cover separation; (c) intermediate flexural crack-induced debonding; (d) critical diagonal shear crack-induced debonding.

Bond performance may be determined in double-shear, single-shear, and notched beam test. In the first two cases, depending on how the force is applied, there can be an indicated push-shear test and pull-shear test. In the push-shear test, clamping the sample is easier; therefore, it is more popular. However, the pull-shear test better reflects the real conditions under which debonding occurs along the tensed surface.

Bond performance is influenced by many factors related to geometry, mechanical properties of materials, environmental conditions, and application conditions. Design methods take into account only some of them. Undoubtedly, the most important factor is the bond area expressed by bond width and bond length. Some bond-strength models introduce the upper limit of the real bond length (called effective bond length) beyond which no further increase in bond force occurs. The second important geometric parameter is the thickness of the composite. The real thickness includes the fibers and the

epoxy matrix. Its direct adoption into the calculations could limit their comparability for SRP tapes of different densities; therefore, the thickness should be taken as the dimension of the cross-sectional area of the fibers distributed over the width of the composite.

The debonding of an SRP composite usually occurs at a thin layer beneath the concrete surface, sometimes with local removal of cover pieces. Concrete is usually the weakest material in a joint; therefore, its strength is another critical factor affecting the bond strength. Typically, compressive strength needs to be determined, less often tensile strength or surface tensile strength. Composite mechanical properties also affect the bond strength. In general, the higher stiffness, the better bond.

The bond strength models are most commonly classified into three categories [12,13]:

- Empirical models, based on the regression of test data, such as Tanaka [14], Hiroyuki and Wu [15], and Maeda [16].
- Fracture mechanics based models, including Taljsten [17], Niedermeier [18], Neubauer and Rostasy [19], Yuan and Wu [20], and Lu et al. [21].
- Design models, usually based on simple assumption, such as Dai et al. [22] Brosens and van Germet [23], Khalifa et al. [24], Yang et al. [25], Adhikary and Mutsuyoshi [26], Sato et al. [27], Chen and Teng [28], DeLorenzis et al. [29], Seracino et al. [30], and Camli and Binici [31].

The length of the anchorage seems to be of key importance for the bearing capacity of the bonded joint. As was earlier mentioned, experimental studies and some fracture mechanics analyses showed that above a certain length (called effective or active bond length), the further increase in load capacity was negligible. To indicate this phenomenon, Toutanji et al. [32] proposed an alternative classification for models independent of the bond length, models not considering the effective bond length, and models considering the effective bond length.

The models analyzed in the article were sorted according to the first classification and summarized in Table 1. Some of these theoretical models have been developed and included in technical guidelines for the design of externally bonded FRP composites. Their examples were also included in the comparisons presented in this manuscript. The design procedures used therein are described in Table 2.

Table 1. Predictive models for the FRP-concrete bond.

Reference	Relationships
Tanaka [14]	$F_{ub} = b_f L_b (6.13 - \ln(L_b))$
Hiroyuki and Wu [15]	$F_{ub} = b_f L_b (5.88 (0.1 L_b)^{-0.669})$
Maeda et al. [16]	$F_{ub} = (110.2 \cdot 10^{-9} E_f t_f) b_f L_e$ $L_e = e^{6.13 - 0.58 \ln 0.001 E_f t_f}$
Taljsten [17]	$F_{ub} = \sqrt{\frac{2 E_f t_f G_f}{1 + \alpha_T}} b_f$ $\alpha_T = \frac{E_f t_f}{E_c t_c}, G_f = 0.14 f'_c (G_f = 0.65 \text{ if } f_{cm} > 46, 2)$
Nidermeier [18]	$F_{ub} = \begin{cases} 0.78 \cdot k_b b_f \sqrt{0.408 f_{ctm} E_f t_f} & \text{if } L_b \geq L_e \\ 0.78 \cdot k_b b_f \sqrt{0.408 f_{ctm} E_f t_f} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$
Neubauer and Rostasy [19]	$k_b = \sqrt{\frac{1.125 \left(2 - \frac{b_f}{b}\right)}{1 + \frac{b_f}{400}}} \geq 1, L_e = \sqrt{\frac{E_f t_f}{4 f_{ctm}}}$ $F_{ub} = \begin{cases} 0.64 \cdot k_b b_f \sqrt{E_f t_f f_{ctm}} & \text{if } L_b \geq L_e \\ 0.64 \cdot k_b b_f \sqrt{E_f t_f f_{ctm}} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$ $k_b = \sqrt{\frac{1.125 \left(2 - \frac{b_f}{b}\right)}{1 + \frac{b_f}{400}}} \geq 1, L_e = \sqrt{\frac{E_f t_f}{2 f_{ctm}}}$

Table 1. Cont.

Reference	Relationships
Yuan and Wu [20]	$F_{ub} = \sqrt{\frac{2E_f t_f G_f}{1 + \alpha_Y}} b_f$ $\alpha_Y = \frac{b_f E_f t_f}{b_c E_c t_c}, G_f = 0.14 f'_c$
Lu et al. [21]	$F_{ub} = \begin{cases} b_f \sqrt{2E_f t_f G_f} & \text{if } L_b \geq L_e \\ b_f \sqrt{2E_f t_f G_f} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$ $G_f = 0.308 \beta_w^2 \sqrt{f_{ct}}, \beta_w = \sqrt{\frac{2.25 - b_f/b_c}{1.25 + b_f/b_c}}$ $L_e = a + \frac{1}{2\lambda_1} \ln \left(\frac{\lambda_1 + \lambda_2 \tan(\lambda_2 a)}{\lambda_1 - \lambda_2 \tan(\lambda_2 a)} \right),$ $\lambda_1 = \sqrt{\frac{\tau_f}{s_0 E_f t_f}}, \lambda_2 = \sqrt{\frac{\tau_f}{(s_f - s_0) E_f t_f}}, a = \frac{1}{\lambda_2} \sin^{-1} \left[0.99 \sqrt{\frac{s_f - s_0}{s_f}} \right],$ $s_f = \frac{2G_f}{\tau_f}, s_0 = 0.0195 \beta_w f_{ct}, \tau_f = 1.50 \beta_w f_{ct}$
Dai et al. [22]	$F_{ub} = (b_f + 7.4) \sqrt{2E_f t_f G_f}$ $G_f = 0.524 f_c^{0.236}$
Brosens and van Germet [23]	$F_{ub} = 0.5 b_f L_b f_{ctm}$
Khalifa et al. [24]	$F_{ub} = \left(110.2 \cdot 10^{-9} \left(\frac{f'_c}{42} \right)^{\frac{2}{3}} E_f t_f \right) b_f L_e$ $L_e = e^{6.13 - 0.58 \ln 0.001 E_f t_f}$
Yang et al. [25]	$F_{ub} = 0.5 f_{ct} \left(0.5 + 0.08 \sqrt{\frac{E_f t_f}{100 f_{ctm}}} \right) L_e b_f$ $L_e = 100 \text{ mm}$
Adhikary and Mutsuyoshi [26]	$F_{ub} = 0.25 f_{cm}^{2/3} b_f L_e$
Sato et al. [27]	$F_{ub} = \begin{cases} (b_f + 7.4) L_e (2.68 f_{cm}^{0.2} t_f E_f \cdot 10^{-5}) & \text{if } L_b \geq L_e \\ (b_f + 7.4) L_b (2.68 f_{cm}^{0.2} t_f E_f \cdot 10^{-5}) & \text{if } L_b < L_e \end{cases}$ $L_e = 1.89 (E_f t_f)^{0.4}$
Chen and Teng [28]	$F_{ub} = 0.427 \beta_p \beta_L \sqrt{f'_c} b_f L_e$ $\beta_p = \sqrt{\frac{2 - b_f/b_c}{1 + b_f/b_c}}, \beta_L = \sin \frac{\pi L_b}{2 L_e} \leq 1, L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_{cm}}}}$
DeLorenzis et al. [29]	$F_{ub} = b_f \sqrt{2.86 E_f t_f}$
Seracino et al. [30]	$F_{ub} = \begin{cases} 0.85 \left(\frac{d_f}{b_f} \right)^{0.25} f_c^{0.33} \sqrt{(b_f + 2d_f) E_f b_f t_f} & \text{if } L_b \geq L_e \\ 0.85 \left(\frac{d_f}{b_f} \right)^{0.25} f_c^{0.33} \sqrt{(b_f + 2d_f) E_f b_f t_f} \frac{L_b}{L_e} & \text{if } L_b < L_e \end{cases}$ $L_e = \frac{\pi}{2 \sqrt{\frac{\tau_f (b_f + 2d_f)}{\delta_f E_f b_f t_f}}}, d_f = 1 \text{ mm}$ $\tau_f = \left(0.802 + 0.078 \frac{d_f}{b_f} \right) f_c^{0.6}, \delta_f = \frac{0.73}{\tau_f} \left(\frac{d_f}{b_f} \right)^{0.5} f_c^{0.67}$ $F_{ub} = b_f \sqrt{\tau_f \delta_u E_f t_f \tanh \left(\frac{\theta L_b}{L_e} \right)}$
Camli and Binici [31]	$L_e = \sqrt{\frac{E_f t_f}{\sqrt{f'_c}}}, \theta = \sqrt{\frac{\tau_f}{\delta_u \sqrt{f'_c}}}, \tau_f = 3.50 f_c^{0.19},$ $\delta_u = f_c^{-0.4} \left(\frac{L_b}{L_e} \right)^{0.8} \left(\frac{b_f}{b} \right)^{0.4}$

Table 2. Relationships for the FRP-concrete bond proposed in the selected technical guidelines (without safety factors).

Document	Relationships
TR55/2000 [33]	$F_{ub} = \begin{cases} 0.5k_b b_f \sqrt{E_f t_f f_{ctm}} & \text{if } L_b \geq L_e \\ 0.5k_b b_f \sqrt{E_f t_f f_{ctm}} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$ $k_b = 1.06 \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{400}}} \geq 1, L_e = \sqrt{\frac{E_f t_f}{2 f_{ctm}}} \geq 500 \text{ mm}$
Fib Bulletin 14/2001 [34]	$F_{ub} = \begin{cases} \alpha c_1 k_c k_b b_f \sqrt{E_f t_f f_{ctm}} & \text{if } L_b \geq L_e \\ \alpha c_1 k_c k_b b_f \sqrt{E_f t_f f_{ctm}} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$ $\alpha = 0.9, k_c = 0.9, k_b = 1.06 \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{400}}} \geq 1 \text{ for } \frac{b_f}{b} \geq 0.33,$ $L_e = \sqrt{\frac{E_f t_f}{c_2 f_{ctm}}},$ $c_1 = 0.64, c_2 = 2.0$
JCI 2003 [35]	$F_{ub} = \begin{cases} \tau_a b_f L_b & \text{if } L_b \geq L_e \\ \tau_a b_f L_e & \text{if } L_b < L_e \end{cases}$ $\tau_a = 0.93 f_{cm}^{0.44}, L_e = 0.125 (E_f t_f)^{0.57}$
SIA 166/2004 [36]	$F_{ub} = 0.5 b_f \sqrt{E_f t_f f_{ctH}}$ $f_{ctH} = 0.3 f_{ck}^{2/3}, L_e = \frac{3\pi}{16} \sqrt{\frac{E_f t_f}{f_{ctH}}}$
CNR-DT200R1/13 [37]	$F_{ub} = \begin{cases} b_f \sqrt{2 E_f t_f G_f} & \text{if } L_b \geq L_e \\ b_f \sqrt{2 E_f t_f G_f} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$ $G_f = k_b k_G \sqrt{f_{cm} f_{ctm}}, k_b = \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{b}}} \geq 1 \text{ for } \frac{b_f}{b} \geq 0.25,$ $k_G = 0.077$ $L_e = \frac{0.25}{2 G_f} \sqrt{\frac{\pi^2 E_f t_f G_f}{2}} \geq 200 \text{ mm}$
Fib Bulletin 90/2019 [38]	$F_{ub} = \begin{cases} k_m k_b b_f \sqrt{2 E_f t_f f_{cm}^{2/3}} & \text{if } L_b \geq L_e \\ k_m k_b b_f \sqrt{2 E_f t_f f_{cm}^{2/3}} \frac{L_b}{L_e} \left(2 - \frac{L_b}{L_e}\right) & \text{if } L_b < L_e \end{cases}$ $k_m = 0.25, k_b = \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{b}}}, L_e = \frac{\pi}{k_b} \sqrt{\frac{E_f t_f}{8 f_{cm}^{2/3}}}$

The following technical standards were considered: British TR55/2000 [33], international *fib* Bulletin 14/2001 [34], Japan JCI 2003 [35], Swiss Code SIA 166/2004 [36], Italian standard CNR-DT200R1/2013 [37], and the newest international *fib* Bulletin 90/2019 [38].

3. Laboratory Test Database

The design methods presented in Tables 1 and 2 were developed for a wide range of FRP composites, based not only on carbon fibers but also on glass, aramid, and basalt fibers. Some of the design parameters and coefficients used in these documents were determined and calibrated on a wide

spectrum of laboratory tests. SRP composites, as newer material, have not been studied so widely. Previous attempts to assess the suitability of formulas for determining the bond of SRPs included the own research of authors [39,40] or were carried out on a relatively small number of samples and prediction models [8].

The database used for the comparison in this work consisted of 434 debonding tests. The data were collected from 11 experimental campaigns reported in the literature, including independently analyzed tests of steel-reinforced epoxy polymers bonded to concrete (237 samples [39,41–45]), and masonry (114 samples [46–49]), and steel-reinforced grout (SRG) bonded to concrete (83 samples [50]). Table 3 summarizes the main geometric and material data available in the research reports used, as well as the corresponding reference and the number of tested specimens. In some of the test reports, tensile strength was not specified. In this case, it was calculated as:

$$f_{ctm} = 0.3(f_{cm} - 8)^{2/3}, \quad (1)$$

Table 3. List of geometry and material properties collected from the available experimental data and used for comparison.

Reference	Number of Tested Specimens	<i>b</i> (mm)	<i>f_{cm}</i> (MPa)	<i>b_f</i> (mm)	<i>t_f</i> (mm)	<i>L_b</i> (mm)	<i>E_f</i> (GPa)
Figeys [41] ¹	7	100	35	95	0.601	150–200	177.6
Mantana [42] ¹	12	191	14.8	51	0.483	102–305	179.1
Mitoldis [43] ¹	8	100	22.4	50–80	0.562	150–300	221.4
Napoli [44] ¹	19	200	15.2–39.7	100	0.084–0.381	150–300	206.6
Ascione [39] ¹	129	200	13–45	20–100	0.084–0.381	100–350	190
Ascione [45] ¹	62	200	19.3–25.6	100	0.084–0.381	100–350	182.1–183.4
Valluzzi [46] ²	63	120	19.8	50	0.231	160	195.1
Panizza [47] ²	3	120	8.24	50	0.227	195	200.2
Grande [48] ²	13	120	38.5	25	0.227	160	190
de Felice [49] ²	21	120	8.2–19.8	50	0.231	195–200	195.1
Napoli [44] ²	14	120	14.7–18.5	50	0.254	200–280	183.4
Ascione [50] ³	83	200	13–40	50–100	0.084–0.254	100–350	182.1–183.4

¹ epoxy matrix and concrete substrate; ² masonry substrate; ³ grout matrix and concrete substrate.

Most of the samples were tested in a single [39,44–46,49,50] and double [42,43,46,48,49] push-shear test, only Figeys [41] used the double pull-shear method. To reflect the test conditions, all the material properties and correction coefficients taken during the calculations were based on mean values. In the case of the CNR-DT200R1/13 standard, a different value of the *k_G* corrective factor for concrete (0.077 mm) and masonry (0.093 mm) was taken into account.

4. Results and Discussion

The graphical comparison of bond models is shown in Figures 2–25 in the order of their presentation in Tables 1 and 2. The types of substrate and adhesive are distinguished by other markers. For SRP composites bonded to concrete, it is ●, for masonry, it is the sign ◆, and for SRG tapes, it is ▲.

Figure 2. Test vs. predicted bond force using the Tanaka model [14].

Figure 3. Test vs. predicted bond force using the Hiroyuki and Wu model [15].

Figure 4. Test vs. predicted bond force using the Maeda et al. model [16].

Figure 5. Test vs. predicted bond force using the Taljsten model [17].

Figure 6. Test vs. predicted bond force using the Nidermeier model [18].

Figure 7. Test vs. predicted bond force using the Neubauer and Rostassy model [19].

Figure 8. Test vs. predicted bond force using the Yuan and Wu model [20].

Figure 9. Test vs. predicted bond force using the Lu et al. model [21].

Figure 10. Test vs. predicted bond force using the Dai et al. model [22].

Figure 11. Test vs. predicted bond force using the Brosens van Germet model [23].

Figure 12. Test vs. predicted bond force using the Khalifa et al. model [24].

Figure 13. Test vs. predicted bond force using the Yang et al. model [25].

Figure 14. Test vs. predicted bond force using the Adhikary et al. model [26].

Figure 15. Test vs. predicted bond force using the Sato et al. model [27].

Figure 16. Test vs. predicted bond force using the Chen and Teng model [28].

Figure 17. Test vs. predicted bond force using the DeLorenzis et al. model [29].

Figure 18. Test vs. predicted bond force using the Seracino et al. model [30].

Figure 19. Test vs. predicted bond force using the Camli and Binici model [31].

Figure 20. Test vs. predicted bond force using the TR 55/2000 model [33].

Figure 21. Test vs. predicted bond force using the fib 14/2001 model [34].

Figure 22. Test vs. predicted bond force using the JCI 2003 model [35].

Figure 23. Test vs. predicted bond force using the SIA 166/2004 model [36].

Figure 24. Test vs. predicted bond force using the CNR-DT200/2013 model [37].

Figure 25. Test vs. predicted bond force using the fib 90/2019 model [38].

Each graph contains a bisector. The point on this line corresponds to the perfect agreement of the prediction model with the tests. The points below the line indicate that the model underestimated the

experiment. This group of results can be considered safe. The points above the bisector mean that the model overestimated the test result and was therefore unsafe.

4.1. Comparison of Models

The first feature visible in the graphs is the scattering of results. The more they were concentrated around the bisector, the more accurate the model. In this respect, the best models were Lu et al. [21] and the newer Chen and Teng [28], Seracino et al. [30], as well as Camli and Binici [31].

The largest dispersion of results concerned the Dai et al. [22], Brosens and van Germet [23], and Adhikari and Mitsuyoshi [26] models. The common feature of the three models was that they did not depend on the anchorage length or the effective anchorage length. This proved the importance of this quantity in the analysis. The Tajlsten [17] model was an exception in this respect.

Another interesting observation concerned the Tanaka [14] and Hiroyuki and Wu [15] models. They undervalued the predicted bond for higher values of an experimentally obtained ultimate bond. This may have resulted from the omission of the concrete strength in the analysis that characterized these two models.

Dai et al. [22], Adhikary and Mitsuyoshi [26], and DeLorenzis et al. [29] were among the models that overestimated the bond capacity. The DeLorenzis model was calibrated on bond tests of CFRP sheets, and this may be the reason for its characteristics. Interesting in this regard are the results based on the Sato et al. model [27] (Figure 15). It underestimated the bond capacity in terms of low forces and, at the same time, dangerously overestimated for higher forces. Groups of models that underestimated the bond included Tajlsten [17], Yuan and Wu [20], Khalifa et al. [24], Yang et al. [25], and the British TR55/2000 standard [33].

The described graph observations were confirmed by the results of the statistical analysis presented in Tables 4–6. The following parameters were used to evaluate and were analyzed in the manuscript bond prediction models: mean value of the predicted, theoretically to measure experimentally bond strength ratio ($F_{ub,predicted} / F_{ub,test}$), standard deviation (SD), and Pearson's correlation coefficient (PCC). Additionally, to evaluate the safety of the prediction, the percentage of results was given. Parameters are listed separately for the SRP bonded to concrete (Table 4), SRP bonded to masonry (Table 5), and SRG bonded to concrete (Table 6).

Table 4. Summary of results—predicted to experimental bond strength ratios for steel-reinforced polymer (SRP) composites bonded to concrete.

Model	Mean	SD	PCC	% Uncertainty
Tanaka [14]	0.699	0.263	0.220	15%
Hiroyuki and Wu [15]	0.746	0.218	0.503	13%
Maeda et al. [16]	1.14	0.241	0.751	66%
Tajlsten [17]	0.761	0.193	0.748	20%
Nidermeier [18]	0.763	0.244	0.629	17%
Neubauer and Rostasy [19]	0.980	0.313	0.629	45%
Yuan and Wu [20]	0.763	0.195	0.747	11%
Lu et al. [21]	0.873	0.234	0.676	27%
Dai et al. [22]	1.55	0.372	0.734	91%
Brosens and van Germet [23]	0.937	0.478	0.408	36%
Khalifa et al. [24]	0.754	0.197	0.729	8%
Yang et al. [25]	0.528	0.166	0.657	0%
Adhikary and Mitsuyoshi [26]	2.00	0.906	0.476	89%
Sato et al. [27]	1.81	1.22	0.573	68%
Chen and Teng [28]	0.882	0.202	0.726	30%
DeLorenzis et al. [29]	1.63	0.389	0.728	95%
Seracino et al. [30]	0.752	0.196	0.716	13%
Camli and Binici [31]	1.14	0.246	0.745	67%
TR55/2000 [33]	0.502	0.197	0.609	3%

Table 4. Cont.

Model	Mean	SD	PCC	% Uncertainty
Fib Bulletin 14/2001 [34]	0.821	0.268	0.632	23%
JCI 2003 [35]	0.941	0.263	0.738	39%
SIA 166/2004 [36]	0.911	0.219	0.756	34%
CNR-DT200R1/13 [37]	0.928	0.264	0.718	43%
Fib Bulletin 90/2019 [38]	0.962	0.233	0.755	45%

In the group of SRP models bonded to concrete, the mean closest to 1.0 can be found in the Brosens and van Germet [23], and Neubauer and Rostasy [19] models; however, it was accompanied by one of the highest standard deviations and correlation coefficients. In this situation, a good agreement of the mean should be considered as aleatory.

Furthermore, after analyzing the values of all statistical parameters, we found that Lu et al. [21] and Chen and Teng [28] models were the most accurate. Similarly, among the technical guidelines, fair exactness ensured JCI 2003, SIA 166/2004, CNR-DT200R1/13, and the fib bulletin 90/2019; they could be successfully used to predict the bond strength of SRP composites to concrete. The older fib bulletin 14/2001 and especially TR55/2000, tended to underestimate the bond capacity too much.

Models by Dai et al. [22], Adhikary and Mitsuyoshi [26], Sato et al. [27], and DeLorenzis [29] not only overestimated the bond prediction but also had a very high percentage of unsafe design.

Table 5. Summary of results—predicted to experimental bond strength ratios for SRP composites bonded to masonry.

Model	Mean	SD	PCC	% Uncertainty
Tanaka [14]	0.911	0.209	0.330	58%
Hiroiyuki and Wu [15]	0.869	0.202	0.339	23%
Maeda et al. [16]	1.34	0.322	0.416	87%
Taljsten [17]	0.764	0.202	0.339	29%
Nidermeier [18]	1.04	0.339	0.215	68%
Neubauer and Rostasy [19]	1.34	0.435	0.215	81%
Yuan and Wu [20]	0.764	0.202	0.339	29%
Lu et al. [21]	1.13	0.277	0.358	74%
Dai et al. [22]	1.87	0.393	0.453	90%
Brosens and van Germet [23]	1.208	0.663	−0.087	71%
Khalifa et al. [24]	0.726	0.232	0.232	16%
Yang et al. [25]	0.719	0.223	0.223	45%
Adhikary and Mutsuyoshi [26]	1.78	0.664	0.116	87%
Sato et al. [27]	1.73	0.499	0.499	87%
Chen and Teng [28]	1.04	0.222	0.441	74%
DeLorenzis et al. [29]	1.91	0.47	0.424	90%
Seracino et al. [30]	0.954	0.218	0.414	68%
Camli and Binici [31]	1.271	0.351	0.380	84%
TR55/2000 [33]	0.655	0.231	0.229	13%
Fib Bulletin 14/2001 [34]	1.20	0.392	0.218	77%
JCI 2003 [35]	0.943	0.238	0.379	65%
SIA 166/2004 [36]	0.954	0.22	0.404	65%
CNR-DT200R1/13 [37]	1.41	0.432	0.232	81%
Fib Bulletin 90/2019 [38]	1.09	0.249	0.411	77%

As shown in Table 5, the general trend for masonry-bonded SRP composites was similar to that for concrete-bonded. Similar models tended to overestimate or underestimate prediction. However, a general increase in the mean of the ratio of predicted to experimentally measured results could be observed. It ranged from one (Taljsten [17], Yuan and Wu [20]) to several dozen percent (Tanaka [14], fib Bulletin 14/2001 [34], and CNR-DT 200 [37]). Only two models showed a decrease in the mean value (Adhikary and Mutsuyoshi [26] and Sato et al. [27]); however, they still overestimated the bond strength, and the result was characterized by the highest standard deviation.

Against the background of all the results in Table 5, the prediction error of the Italian Standard CNR-DT200R1/13 may be surprising. Average predictions increased by more than 50%. It results most likely from assuming an overestimated value of the k_G coefficient. Based on Appendix D of the cited standard, it was adopted as a mean value $k_G = 0.093$ mm, but it was characterized by high variation (recommended for design, 5% fractile is 0.031 mm).

Table 6. Summary of results—predicted to experimental bond strength ratios for steel-reinforced grout (SRG) composites bonded to concrete.

Model	Mean	SD	PCC	% Uncertainty
Tanaka [14]	0.882	0.344	0.049	27%
Hiroiyuki and Wu [15]	0.984	0.277	0.526	42%
Maeda et al. [16]	1.31	0.57	−0.174	54%
Taljsten [17]	0.848	0.499	−0.241	35%
Nidermeier [18]	0.812	0.482	−0.264	31%
Neubauer and Rostasy [19]	1.043	0.619	−0.264	50%
Yuan and Wu [20]	0.851	0.501	−0.241	35%
Lu et al. [21]	0.965	0.499	−0.274	50%
Dai et al. [22]	1.71	0.832	−0.245	69%
Brosens and van Gemet [23]	1.16	0.802	0.099	46%
Khalifa et al. [24]	0.861	0.539	−0.215	27%
Yang et al. [25]	0.589	0.339	−0.248	8%
Adhikary and Mutsuyoshi [26]	2.68	1.43	0.190	96%
Sato et al. [27]	1.41	1.09	−0.354	54%
Chen and Teng [28]	1.01	0.52	−0.274	50%
DeLorenzis et al. [29]	1.83	0.850	−0.210	77%
Seracino et al. [30]	0.821	0.441	−0.275	27%
Camli and Binici [31]	1.39	0.52	0.146	62%
TR55/2000 [33]	0.554	0.332	−0.061	8%
Fib Bulletin 14/2001 [34]	0.937	0.007	−0.261	42%
JCI 2003 [35]	1.02	0.604	−0.259	50%
SIA 166/2004 [36]	1.01	0.541	−0.244	50%
CNR-DT200R1/13 [37]	1.02	0.595	−0.220	50%
Fib Bulletin 90/2019 [38]	1.08	0.58	−0.273	50%

Evaluating only the mean parameter presented in Table 6, the assessment of the possibility of using the analyzed models in predicting the SRG bond would be similar to the SRP. However, a large standard deviation, and especially the negative correlation coefficient, excluded the applicability of those models. The analysis of the experimental measures used for the comparison showed their low sensitiveness to the strength of concrete. This may be due to significantly worse properties of grout adhesives compared to epoxies. Under these conditions, delamination may occur in the adhesive layer. The adhesive was the weakest element, and its strength properties determined the bond capacity. None of the analyzed models in this manuscript took into account the properties of the adhesive, and this may have caused a large dispersion of the results.

4.2. Precision of Predictions Compared to CFRP Composites

The accuracy of the prediction models for SRP bonded to concrete was not any less than that for CFRP composites. Table 7 shows a comparison of prediction error for selected models (according to mean ratios given in Table 4) and is available in the literature results of similar assessments for CFRP strips. In most cases, the differences did not exceed ten percentage points, and for the previously favored models, Lu et al. [21] and Chen and Teng [28] were practically identical. Similarly to the SRP, can be found models that tended to overestimate and underestimate the results. This proved that SRP and CFRP composites were very similar in terms of bond strength.

Table 7. Predicted to experimental bond strength ratios for SRP composites and carbon fiber reinforced polymer (CFRP) strips bonded to concrete.

Model	SRP	CFRP		
		Tutanji et al. [32]	Wu et al. [51]	Anil et al. [52]
Tanaka [14]	0.699	0.48	0.68	0.98
Hirokyu and Wu [15]	0.746	0.476		0.94
Maeda et al. [16]	1.14	0.929	0.95	1.25
Talijsten [17]	0.761	0.761		
Nidermeier [18]	0.763	0.73	0.87	
Neubauer and Rostasy [19]	0.980	1.12	1.10	1.23
Yuan and Wu [20]	0.763	0.763		
Lu et al. [21]	0.873	0.819		
Dai et al. [22]	1.55	1.49		
Brosens and van Gemert [23]	0.937	0.718		
Khalifa et al. [24]	0.754	0.798	0.92	0.76
Yang et al. [25]	0.528	0.841	0.94	0.89
Adhikary Mutsuyoshi [26]	2.00	1.19		
Sato et al. [27]	1.81	1.28	1.45	1.03
Chen and Teng [28]	0.882	0.857	0.89	0.91

4.3. Assessment of Design Guidelines

To evaluate the reliability of design guidelines for the bond prediction of SRP, a demerit points classification proposed by Collins [53] was used. This scale allowed considering the safety and accuracy of design procedures by weighting the ratio between the ultimate bond strength, estimated theoretically and measured experimentally ($F_{ub,predicted}/F_{ub,test}$). Table 8 presents the classification adopted in this study based on the original values proposed by Collins.

Table 8. The demerit points classification (DPC) scale.

Classification Category	$F_{ub,predicted}/F_{ub,test}$	DPC Points
Extremely dangerous	≥ 2.00	10
Dangerous	1.15–2.00	5
Appropriate and safe	0.85–1.15	0
Conservative	0.5–0.85	1
Extremely conservative	<0.5	2

The results of bond comparisons were classified into appropriate categories, as shown in Table 8, and the products were then multiplied by the appropriate demerit points classification (DPC) and summed up. The number of results assigned to the categories and the summed DPC is shown in Tables 9 and 10. A lower overall DPC means that the model under consideration was more reliable.

In the case of SRP bonded to concrete, the lowest total demerit points (111 points) presented the Swiss Standard SIA 166/2004. *Fib* bulletin 14 achieved a slightly worse result (115 points); however, this was mainly due to a small number of overestimated results. In terms of the number of the most accurate predictions, there were SIA166, Italian code CNR-DT200, and *fib* bulletin 90.

Table 9. Classification of technical guidelines according to Collins' DPC scale; SRP composites bonded to concrete.

	>2	1.15–2	0.85–1.15	0.5–0.85	<0.5	Total DPC
TR55/2000 [33]	-	-	6	36	49	134
Fib Bulletin 14/2001 [34]	-	11	31	38	11	115
JCI 2003 [35]	-	20	33	34	4	142
SIA 166/2004 [36]	-	15	41	34	1	111
CNR-DT200R1/13 [37]	-	20	37	29	5	139
Fib Bulletin 90/2019 [38]	-	21	40	29	1	136

Table 10. Classification of technical guidelines according to Collins' DPC scale; SRP composites bonded to masonry.

	>2	1.15–2	0.85–1.15	0.5–0.85	<0.5	Total DPC
TR55/2000 [33]	-	1	11	13	5	28
Fib Bulletin 14/2001 [34]	3	18	6	2	1	124
JCI 2003 [35]	-	15	9	5	1	82
SIA 166/2004 [36]	-	14	10	4	2	78
CNR-DT200R1/13 [37]	8	16	4	1	1	163
Fib Bulletin 90/2019 [38]	-	20	7	2	1	104

Among the prediction guidelines concerning the SRP bonded to masonry, the lowest number of demerit points was obtained by the British standard TR55/20000 (28 points). Taking into account its strong tendency to lower the results (shown in Table 5), the Swiss Standard SIA 166/2004 should be assessed higher, despite the significantly higher number of demerit points (78 points). The Italian Standard CNR-DT200 was the most unfavorable in this comparison, mainly due to the previously described problem of overestimated correction factor k_G .

5. Conclusions

Although all evaluated models were developed for composites reinforced with organic (mainly carbon and glass) fibers, the obtained results of comparisons showed surprisingly good compatibility for ultra-high-strength steel textile composites.

Most of the assessed models should be considered moderately conservative, with the ratio of predicted to experimental bond strength in the range of 0.5–0.85. As shown in Table 7, this trend also applied to CFRP composites, and in most comparisons, the results obtained for SRP can be assessed as more accurate.

The best accuracy was guaranteed by Lu et al.'s proposal, [21] Chen and Teng's proposal [28], and technical guidelines recommendations (except TR55/2000 [33]). This proved the predominance of models calibrated on a very large number of different samples.

Among all the analyzed models, there were proposals whose results differed significantly from the test results. In a few cases, the predicted to experimental bond strength ratio exceeded the risky limit of 1.15. The worst and most unsafe were the proposals of Dai et al. [22], Adhikari and Mitsuyoshi [26], Sato et al. [27], and De Lorenzis et al. [29]. These models should not be used to determine the bond strength of SRP composites.

The highest compliance was obtained in the analysis of SRP composites bonded to concrete. This was because most of the tested models were developed for epoxy-bonded concrete strengthening systems. In the case of bonding to masonry, the predicted to experimental bond strength ratios were several percentage points higher. Nevertheless, most of the analyzed models could still be considered safe. Apart from the previously mentioned, the Maeda et al. [16], Brosens and van Germet [23], and Camli and Binici [31] models should not be used in this case.

The classification of technical guidelines with the use of the DPC scale as the most universal, distinguished the Swiss standard SIA166/2004 [36] and the latest fib bulletin 90/2019 [39]. The TR55/2000 [33] guideline seemed too conservative. The Italian standard CNR-DT200R1/13 [37], in the case of masonry substrate, estimated too many results classified as dangerous. Perhaps this was the effect of taking the overestimated value of the k_G coefficient in the analysis.

The last conclusion concerned SRG composites. The results obtained from the analysis were inconclusive. They should be extended to a larger experimental database.

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Nomenclature

b	(mm)	concrete width
b_f	(mm)	FRP (SRP) width
E_c	(MPa)	elastic modulus of concrete
E_f	(MPa)	elastic modulus of composite (along fibers)
f_c, f_{cm}	(MPa)	concrete compressive strength
f_{ctm}	(MPa)	concrete tensile strength
F_{ud}	(N)	debonding force
G_f	(MPa·mm)	fracture energy
L_b	(mm)	bond length
L_e	(mm)	effective bond length
k_b, β_p, β_w		geometrical parameter
t_c	(mm)	concrete thickness
t_f	(mm)	FRP (SRP) composite thickness
α_T, α_Y		stiffness ratio
τ_f	(MPa)	bond strength

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