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Fan-to-sheet failure mode of FRP anchors

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Abstract
The use by practicing engineers of Fibre Reinforced Polymer (FRP) anchors in combination with Externally Bonded Reinforcements (EBR) is increasing. FRP anchors are typically used to prevent premature FRP-to-concrete debonding and/or to ensure the continuity of the load path from the FRP sheet into the concrete substrate. Recently proposed design models for most failure modes associated with FRP anchors, such as concrete cone failure and fibre rupture failure, are based on relatively large databases of test results, which ensures the validity of these models. This situation is not the applicable for FRP-to-sheet failure, which is typically triggered by insufficient bond surface and has not received in-depth research attention to date.
The available data on the fan-to-sheet failure mode have been compiled together along with new data provided by the authors, with this data critically analysed in a quantitative and qualitative manner. Models pertaining to this failure mode are proposed, identifying strengths and shortcomings. The models are then used to statistically assess the available database and a final model is proposed, identifying areas in need of further research.

Keywords: FRP anchors, FRP strengthening, premature debonding, bond, anchorage, concrete, spike anchors

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Introduction

Fibre Reinforced Polymer (FRP) anchors are bundles of fibres that, after being saturated with epoxy, in Externally Bonded Reinforcement (EBR) systems have one end introduced into the structure and the other end splayed out and bonded to the FRP sheet or plate. The part inside the structure is referred to as the anchor dowel, while the part outside is typically called the anchor fan or the anchor splay, as illustrated in Figure 1. FRP anchors are used to prevent or delay premature debonding of the FRP sheet and/or to ensure continuity of the load path from the sheet into the structure [1]. While other failure modes have been investigated to various levels of detail, and predictive models have been proposed [2]–[4], the fan-to-sheet failure mode illustrated in Figure 1 has received little research attention so far. A simple model based on the bond strength observed in a limited number of experimental tests was proposed [5], while two complex mechanics-based model were proposed for FRP-to-FRP connections, but the applicability for anchors is unknown [6]. The motivation of the research reported herein was to compile all the available research on fan-to-sheet failure, complement it with a few more datapoints generated by the authors, and verify whether either of the two previously developed models [5], [6] can be further improved.

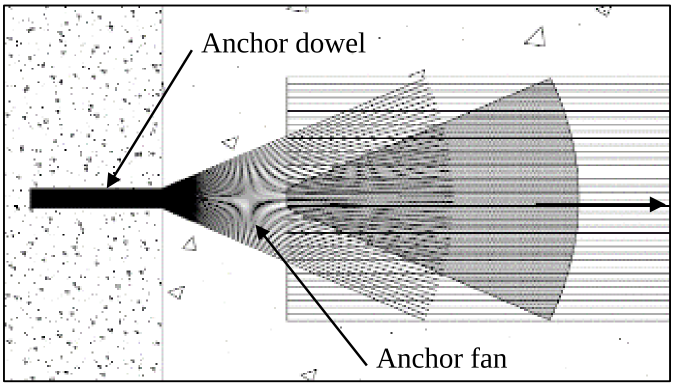

Figure 1 FRP anchor exhibiting fan-to-sheet debonding failure mode

Experimental results

All datapoints used in this study are reported in Table 1 for single layer bond and in

Table 2 for double layer bond, i.e. with the anchor fan sandwiched between two FRP sheets. The data consists of details of the published reference, the specimen name, the area of the fan in cm^2, the peak load (kN) at which fan-to-sheet debonding occurred, and the bond stress (MPa), defined as the peak load over the bond area. Kanitkar [5] proposed to use a minimum bond strength of 35 percent of the bond shear strength of the resin, with a maximum value of 5 MPa if the bond shear strength of the resin is not available. This value is in general agreement with other recommendations [7]. The bond strength from almost all the studies reported in Table 1 and

Table 2 is below the 5.1 MPa baseline but, because those studies were not focused on fan-to-sheet debonding, the properties of the resin were not disclosed and the curing conditions are unknown, making it difficult to judge the reliability of these results.

Table 1 Data for single bond layer

Ref	Specimen name	A_{bond} (cm^2)	Peak load (kN)	σ_{bond} (MPa)	Ref	Specimen name	A_{bond} (cm^2)	Peak load (kN)	σ_{bond} (MPa)
[8]	s15-2a000y-12	150	48.7	3.2	‡	7	126	73.3	5.8
[8]	s15-2a150n-12	150	34.9	2.3	‡	8	126	85.1	6.8
[8]	s15-2b150y-12	150	57.5	3.8	‡	9	126	76.3	6.1
[8]	s15-2b150n-12	150	38.8	2.6	‡	10	126	73.1	5.8
[8]	s15-2c150n-12	150	48.4	3.2	‡	11	126	89.5	7.1
[8]	s15-2A150h-10	150	46.7	3.1	‡	12	126	98.3	7.8
[8]	s20-2b150h-15	200	58.6	2.9	‡	13	126	83.2	6.6
[9]	s1-100-2	14	3.0	2.1	‡	14	126	69.3	5.5
[9]	s2-200-2	14	4.0	2.8	‡	15	126	81.9	6.5
[5]	S1	65	54.0	8.3	‡	16	126	97.0	7.7
[5]	S2	65	60.7	9.3	‡	17	126	86.9	6.9
[5]	S3	65	69.8	10.7	‡	18	168	112.6	6.7
[5]	S4	65	64.1	9.9	‡	19	168	102.5	6.1
[5]	S5	65	69.1	10.6	‡	20	168	122.6	7.3
[5]	S6	65	73.1	11.2	‡	21	168	119.3	7.1
†	n1a-200	200	53.9	2.7	‡	22	168	129.4	7.7
†	n1b-300	450	70.5	1.6	‡	23	207	119.1	5.8
†	n1c-250	313	23.6	0.8	‡	24	207	120.1	5.8
†	n1d-250	313	67.1	2.1	‡	25	207	139.0	6.7
†	n1e-275	111	30.4	2.7	‡	26	207	126.5	6.1
†	n1f-205	156	38.5	2.5					

† New data points from del Rey Castillo, and ‡ New data points from Kanitkar

Table 2 Data for double bond layer

Ref	Specimen name	A_{bond} (cm^2)	Peak load (kN)	σ_{bond} (MPa)	Ref	Specimen name	A_{bond} (cm^2)	Peak load (kN)	σ_{bond} (MPa)
[10]	N5H1.4Mc	24	64.1	26.6	†	n2f-350	1225	58.0	0.5
[10]	B5L1.4Md	24	40.5	16.8	†	n2g-350	1225	114.5	0.9
[10]	B5H1Md	24	67.6	28.1	†	n2h-240	360	33.8	0.9
[11]	R-1	130	54.3	4.2	†	n2i-240	360	31.0	0.9
[11]	R-2	130	55.4	4.3	†	n2j-350	1225	180.2	1.5
[11]	R-3	130	48.9	3.8	†	n2k-250	170	105.0	6.2
[11]	R-4	130	48.0	3.7	†	n2l-300	900	164.5	1.8
†	n2a-150	113	63.1	5.6	‡	27	207	145.1	7.0
†	n2b-300	450	150.6	3.3	‡	28	207	145.5	7.0
†	n2c-200	400	61.7	1.5	‡	29	207	147.2	7.1
†	n2d-200	400	51.1	1.3	‡	30	207	148.0	7.2
†	n2e-250	625	63.5	1.0	‡	31	207	146.7	7.1

† New data points from del Rey Castillo, and ‡ New data points from Kanitkar

Design model

Revised Kanitkar model

The model proposed by Kanitkar was based on the shear strength of a resin with a tensile strength of 55 MPA, but the resin strength in the del Rey Castillo data was 25 MPa as obtained from tests done in accordance with the pertinent ASTM standard [12]. If a ratio of the resin tensile strength is used instead of a ratio of shear strength, the result is 10.8% and 12.2% for del Rey and Kanitkar respectively. Therefore, a suggestion is made to use 10% of the tensile strength as bond strength if the bond shear strength is not available, resulting in equation (1). It is important to note that this model does not consider anchor shape or dimensions.

$$V_{sb} = 0.35\tau_r A_{fan} \tag{1a}$$

If τ_r is not available,

$$V_{sb} = \max\begin{cases} 5A_{fan} \\ 0.1\sigma_r A_{fan} \end{cases} \tag{1b}$$

Where:

V_{sb} = fan-to-sheet failure load [kN]

τ_r = bond shear strength of the resin [MPa]

σ_r = tensile strength of the resin [MPa]

A_{fan} = area of the fan [mm^2]

Revised Singh model

Singh et al. developed two models, but only the simplified model is used for simplicity. First the critical bond length needs to be calculated using equation (2) for singe lap bonded anchor fans and equation (3) is used for double lap bonded anchor fans (i.e. anchor fan sandwiched between two FRP sheets). Once the critical bond length is known the fan-to-sheet failure load can be calculated with equation 4 for single lap bonded anchor fans and with equation 5 for double lap bonded anchor fans.

$$L_{cr}^{sg} = \frac{3\sigma_f t_f}{2\sigma_r} \tag{2}$$

$$L_{cr}^{db} = \frac{2\sigma_f t_f}{\sigma_r} \tag{3}$$

$$V_{sb}^{sg} = \begin{cases} 0.4\sigma_r b_f L & L < L_{cr} \\ 0.6\sigma_f b_f L & L \geq L_{cr} \end{cases} \tag{4}$$

$$V_{sb}^{db} = \begin{cases} 0.6\sigma_r b_f L & L < L_{cr} \\ 1.2\sigma_f b_f L & L \geq L_{cr} \end{cases} \tag{5}$$

Where:

L_{cr}^{sg} = is the critical bond length of singly bonded fans [mm]

L_{cr}^{db} = is the critical bond length of doubly bonded fans [mm]

σ_f = tensile strength of the FRP [MPa]

t_f = thickness of FRP [mm]
σ_r = tensile strength of the resin [MPa]
V_{sb}^{sg} = fan-to-sheet failure load for singly bonded fans [kN]
V_{sb}^{db} = fan-to-sheet failure load for doubly bonded fans [kN]
b_f = width of the anchor fan [mm]
L = length of the anchor fan [mm]

Because the resin properties were not reported in the literature, only the data from the authors could be used to assess how the revised Singh model predicts the failure load observed in the experiments. The load calculated using the above revised Singh model is 0.8 times the experimental value for single lap bonded anchor fans using Kanitkar's data and is 2.7 times the experimental value using the del Rey Castillo data. The discrepancy is even more significant for double lap bonded anchor fans, with the ratio between predicted and experimental values being 1.1 for the Kanitkar's data and 4.6 for the del Rey Castillo's data. The use of this model is therefore not recommended for anchors, as the model cannot reliably predict the fan-to-sheet failure load.

Conclusions

Two methods to calculate the fan-to-sheet failure load are proposed, one based on a percentage of the tensile or the shear strength of the resin and a second one using a complex model based on fracture mechanics. The revised Kanitkar model described in Equations 1a and 1b can be safely used to calculate the fan-to-sheet failure load but does not consider anchor geometry. The revised Singh model does not accurately predict the data, and therefore is not recommended for anchors until further research is done.

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