APPLICATION OF AN ANALYTICAL MODEL TO ESTIMATE THE CONTRIBUTION OF FRP ANCHORS ON FRP-TO-CONCRETE ANCHORED JOINTS

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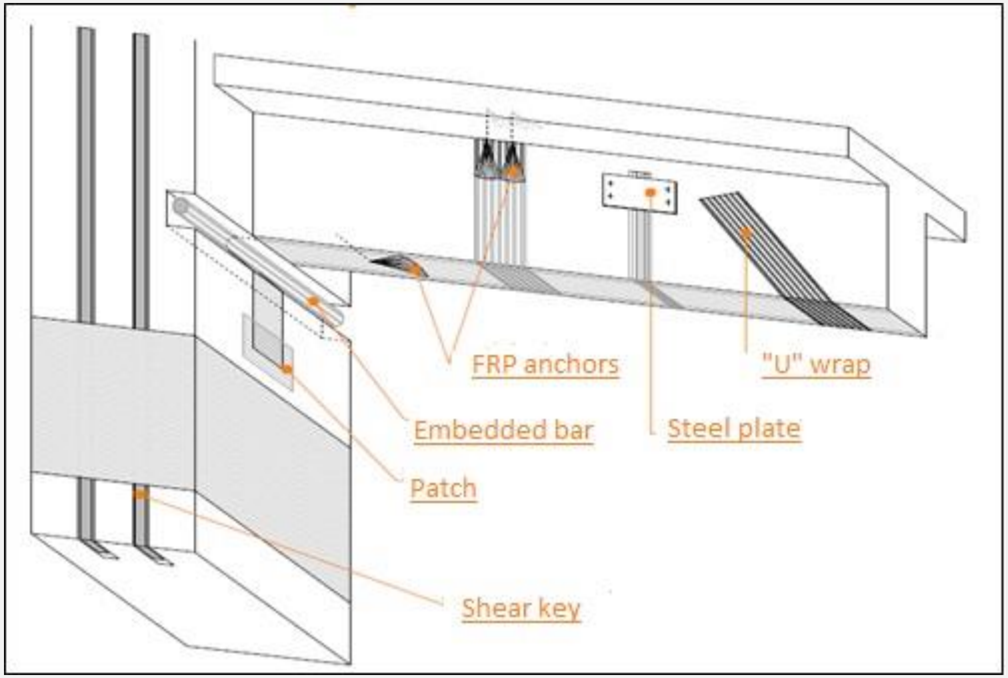
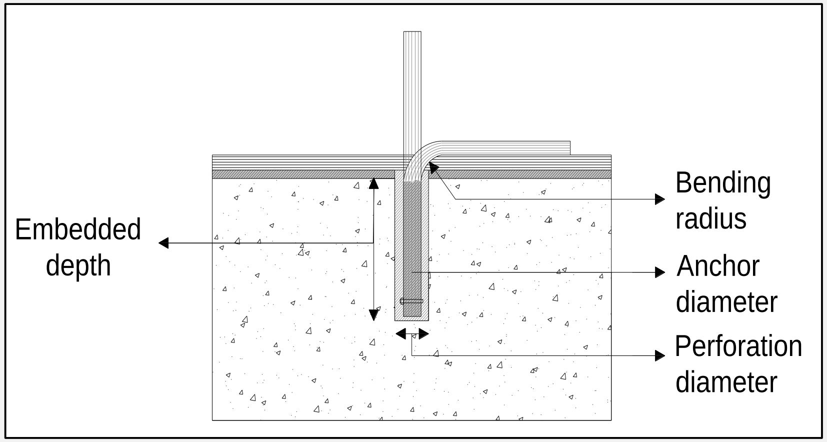
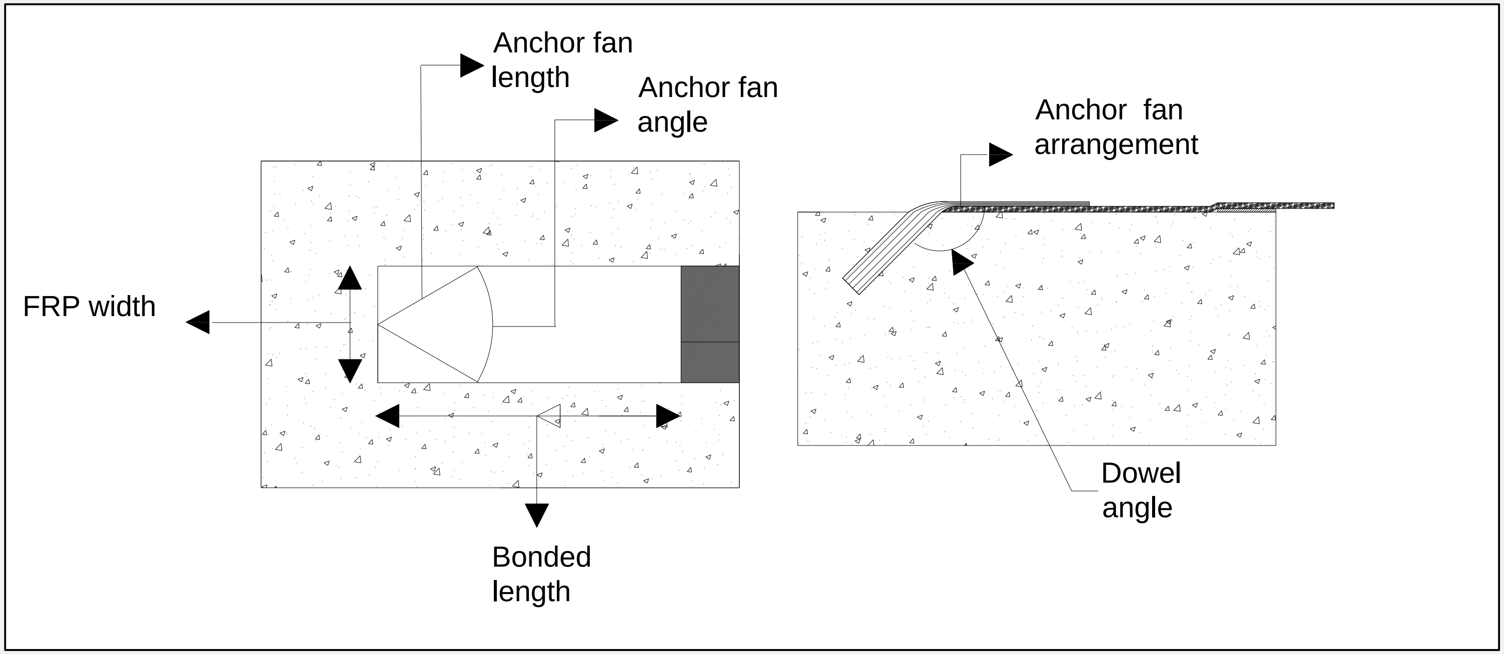
1. FRP reinforcements- Anchorage techniques

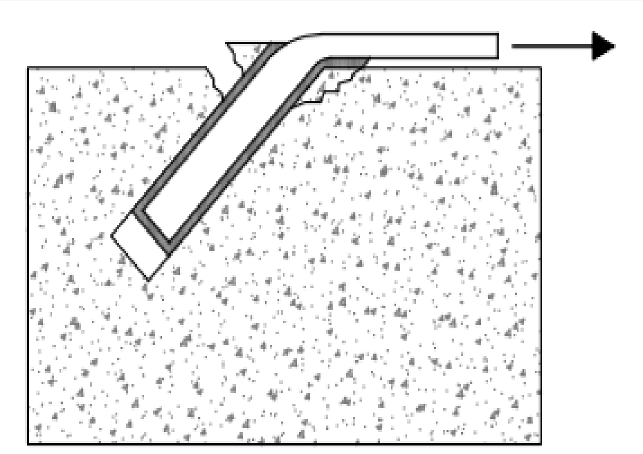


2. Parameters involved in anchor´s behavior

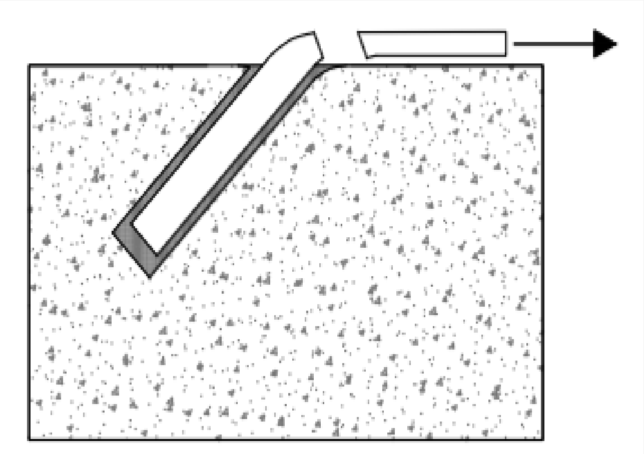




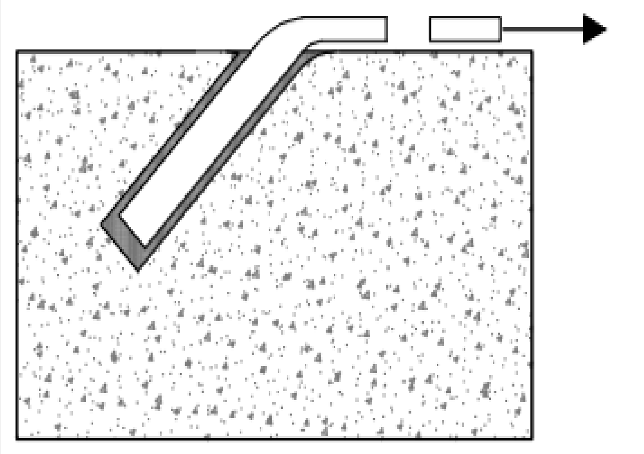
3. Failure modes



ADHERENT/MIXED FAILURE



BENT FIBRE RUPTURE



TENSILE FIBRE RUPTURE

4. Existing models for anchor´s strength

Adherent Strength

$$P_{mix} = \tau_u \cdot \pi \cdot d_0 \cdot h_{emb}$$

τ_u= shear strength
d_0 = perforation diameter
h_{emb} = embedment depth

Tensile Strength

$$P_{\mathrm{ult}} = f_{FRP} \cdot \pi \cdot (R_a)^2$$

f_{FRP} = tensile strength of FRP composite (MPa)
R_a = anchor diameter

$$P_{\mathrm{ult}} = w_{fib} \cdot t_{fib} \cdot f_{fib}$$

w_{fib} = width of fibre sheet used for anchors construction
t_{fib} = thickness of fibre sheet used for anchors construction
f_{fib} = tensile strength of fibre sheet (MPa)

4. Existing models for anchor´s strength

Villanueva et al. (2017)

$$\frac{p_{dob}}{P_{ult}} = (0.3 \cdot \frac{h_{emb}}{heff} + 0.05 \cdot r_b \cdot \left(\frac{\alpha}{\frac{\pi}{2}}\right))$$

Sun et al. (2018)

$$f_{fb} = [(0.06 \cdot r_b + 0.21) + 0.22 \cdot S^{-1.15} + 0.23\left(\frac{\alpha_d}{90°} - 1\right)] \cdot f_{fu}$$

Del Rey et al. (2019)

$$N_{fr} = 2.2 \cdot E_{FRP} \cdot \varepsilon_{FRP} \cdot A_{dowel}{}^{0.62} \cdot \left(\frac{90° - \alpha}{90°}\right)$$

4.1 Anchor´s strength

Geometrical parameters considered

Author	Concrete	Specimen Geometry					Reinforcement									
	f´c	d0	hemb	α	β		wfrp					tfro	Efrp	εfrp	T.S.
				α °	Según del Rey		mm					mm	MPA	mm/mm	MPA
Zhang & Smith (2011-2013)	47,2	14	40	90	30	37	50	75	100	125	150	0,393	224.500	0,015	3065
Villanueva et al.	42,6	20	100	135	30,00		150					0,129	220.000	0,017	3200
Cortez et al.	26	20	100	135	30	37,50	100	200	-			0,129	220.000	0,017	3200

Author	Anchor							rb	Ratio Sr				
	Wfrp	tfrp	Adowel	T.S.	Efrp	εfrp	Rdob						
	mm	mm		MPA	MPA	mm/mm	mm		Sr1	Sr2	Sr3	Sr4	Sr5
Zhang & Smith (2011-2013)	200	0,131	113,097	3065	224.500	0,015	3	0,250	1,39	0,92	0,69	0,55	0,46
Villanueva et al.	-	-	78,540	1900	240.000	0,020	25	2,500	2,410				
Cortez et al.	-	-	78,540	1900	240.000	0,020	35	3,50	3,61	1,81	1,81	0,90	

4.1 Anchor´s strength

Adherent strength

Author	T.S.	A.S.	Villanueva et al.	Del Rey et al.		Sun et al.				
	kN	kN	R_{ben} (kN)	R_{ben} (kN)		R_{ben} (kN)				
Zhang & Smith (2011-2013)	83,52	16,71	7,75	34,05	33,13	31,41	38,90	46,79	54,98	63,42
Villanueva et al. (2017)	149,23	59,69	48,62	41,69	-	82,82	-	-	-	-
Cortez et al.	149,23	59,69	55,34	41,69	36,48	87,33	96,46	96,46	103,33	

Tensile strength

Bending zone strength according to the models analysed

4.2 Bending-zone strength

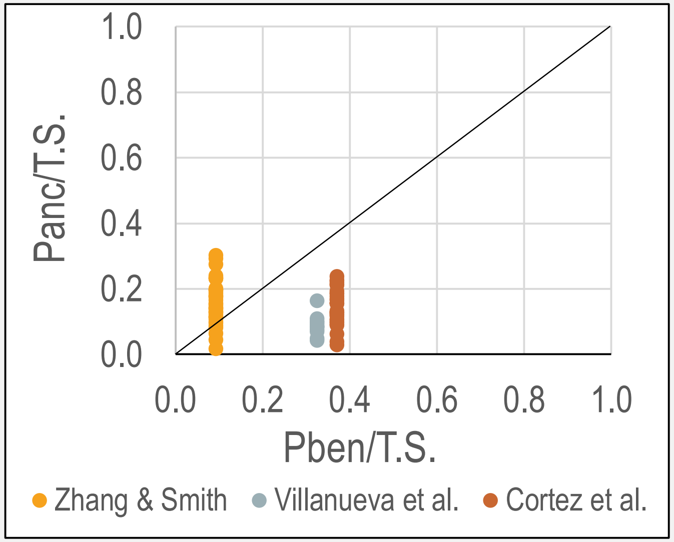
Pjoint= Pdb + Panch
(From experimental results of database)

$\frac{p_{bend}}{P_{últ}}$ "Theoric" based on results of the models

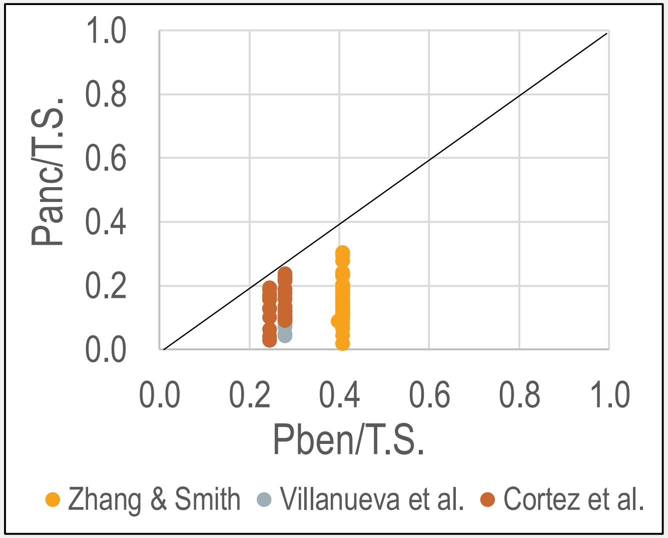
Author	Ranc/T.S.	Villanueva et al.	Del Rey et al.		Sun et al.				
Zhang & Smith (2011-2013)	0,02 - 0,30	0,09	0,41	0,40	0,38	0,47	0,56	0,66	0,76
Villanueva et al. (2017)	0,04 – 0,17	0,33	0,28		0,56				
Cortez et al.	0,03 – 0,24	0,37	0,28	0,24	0,59	0,65	0,65	0,69	

$\frac{p_{anc}}{P_{últ}}$ "Real" based on experimental results

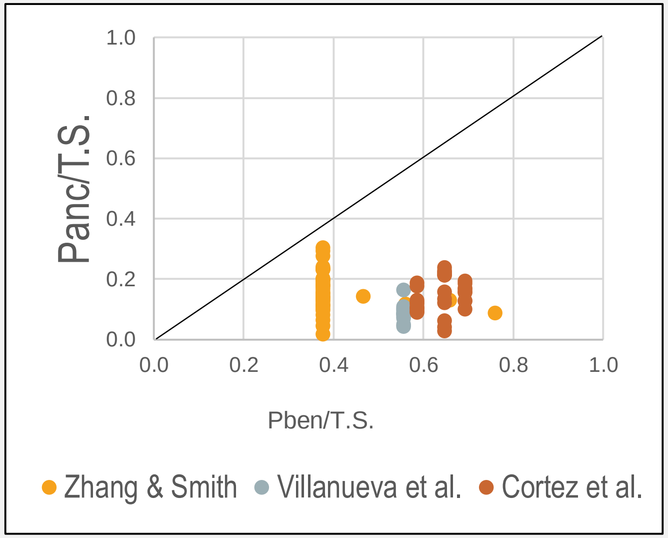
4.2 Bending-zone strength



Villanueva et al.



Del Rey et al.



Sun et al.

4.2 Bending-zone strength

$\frac{p_{anc}}{P_{bend}}$	Anchor´s experimental strength / Anchor´s bending zone strength (models)

Author	Villanueva et al. (2017)			Sun et al. (2018)			Del Rey et al. (2019)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Zhang & Smith (2011-2013)	0,21	3,28	1,72	0,05	0,81	0,41	0,05	0,75	0,39

- 91% of the experimental results are higher than the bent strength predicted by Villanueva´s expression.
- Sun et al. and Del Rey et al. overestimate anchor´s bent strength for the connectors employed by Zhan & Smith.

4.2 Bending-zone strength

$\frac{p_{anc}}{P_{bend}}$ Anchor´s experimental strength / Anchor´s bending zone strength (models)

Author	Villanueva et al. (2017)			Sun et al. (2018)			Del Rey et al. (2019)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Villanueva et al. (2017)	0,13	0,51	0,27	0,08	0,3	0,16	0,15	0,59	0,32

- The three models overestimate the anchor´s strength for the results obtained in the experimental campaign by Villanueva et al.
- Most specimens failed due to tensile ruptura of the reinforcement impeding the anchors to achieve their full capacity.

4.2 Bending-zone strength

$\frac{p_{anc}}{P_{bend}}$	Anchor´s experimental strength / Anchor´s bending zone strength (models)

Author	Villanueva et al. (2017)			Sun et al. (2018)			Del Rey et al. (2019)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Cortez et al.	0,08	0,64	0,39	0,05	0,37	0,23	0,12	0,85	0,55

- The three models overestimate the anchor´s strength for the results obtained in the experimental campaign by Cortez et al.
- Some design parameters affect the performance of the joint strength for the same anchor´s design.
- The position of the anchor with respect to the loaded and unloaded end has a strong influence on the performance of the anchored joint.

4.3 Anchored joint strength

$$P_{joint} = P_{db} + \frac{Llib}{175} \cdot P_{anc}$$

$$P_{jointreal}/P_{jointpred}$$

Campaign	$P_{joint\ real}/P_{joint\ pred}$								
	Villanueva et al. (2017)			Sun et al. (2018)			Del Rey et al. (2019)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Zhang & Smith (2011-2013)	0,83	1,76	1,25	0,39	1,00	0,61	0,39	1,29	0,65

- 94% of the experimental anchored joint strengths exceed the predicted ones when the anchor´s strength is calculated with Villanueva´s expression.
- Sun et al. and Del Rey et al. overestimate still overestimate the anchor´s contribution.

$$P_{joint} = P_{db} + \frac{Llib}{175} \cdot P_{anc}$$

$$P_{jointreal}/P_{jointpred}$$

Campaign	$P_{joint\ real}/P_{joint\ pred}$								
	Villanueva et al. (2017)			Sun et al. (2018)			Del Rey et al. (2019)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Villanueva et al. (2017)	0,69	0,95	0,79	0,54	0,74	0,62	0,73	1,01	0,84

- All values of the predicted anchored joint strengths are higher than the experimental results for all the specimens since the joints presented a premature tensile failure in the reinforcement.

4.3 Anchored joint strength

$$P_{joint} = P_{db} + \frac{Llib}{175} \cdot P_{anc}$$

$$P_{jointreal}/P_{jointpred}$$

Campaign	$P_{joint\ real}/P_{joint\ pred}$								
	Villanueva et al. (2017)			Sun et al. (2018)			Del Rey et al. (2019)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Cortez et al.	0,70	2,12	1,25	0,52	2,12	1,07	0,45	2,12	1,35

- There is a significant variation between the highest and lowest value for the ratio, due to the different geometrical configurations considered in the experimental campaign.
- The experimental anchored joint strength is higher than the predicted one with the anchor´s strength obtained with the three different expressions considered in most of the cases.
- The expression predicts the same strength for anchors in the same position with respect to the loaded end of the joint despite the anchor fan position with respect to the reinforcement.

Anchor´s strength

- Anchor´s strength is highly influenced by its geometrical configuration, manufacturing and installation processes.
- The three expressions evaluated to estimate the anchor´s bending strength overestimate anchors capacity compared to the experimental results considered. This may be due to the reduction in anchor´s resistance when interacting with the reinforcement.
- The unitary resistance of the connector can be considered as: $P_{anc} = min\left\{P_{mix}, \frac{P_{dob}}{P_{ult}}, 0{,}6 * P_{ult}\right\}$
- Expressions to estimate anchor´s contribution to the anchored joint strength must consider the geometrical parameters related to the anchor and those related to the support-reinforcement. And should also take into account the anchor-reinforcement interaction.

Anchored joint strength

The expression proposed by Villanueva et al. for predicting the anchored joint strength has the following limitations:

- It is not applicable for anchors located at the unloaded end of the joint.
- Maximum load was proved to depend on both bonded lengths (in front and behind the anchor).
- For anchors located at the same position with respect to the loaded end the expression predicts the same joint strength.
- The influence of the anchor position with respect to the reinforcement is not considered.

Authors are currently working to readjust it.

Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos

POLITÉCNICA

Thank you for your attention

Departamento Ingeniería Civil: Construcción