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RELIABILITY ANALYSIS OF MODELING CONCRETE-FILLED FRP TUBES UNDER FLEXURAL LOADING FOR BRIDGE APPLICATIONS

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Abstract: Concrete-filled fiber-reinforced polymer (FRP) tubes (CFFTs) are very effective in civil engineering infrastructure including bridges. Considerable research has been performed on the behavior of CFFTs. However, a broad statistical study is required to investigate uncertainty of variables and recommend resistance factors for design applications based on AASHTO design guideline for CFFTs. In this paper, an analytical procedure is presented to compute flexural capacity of CFFTs. Also, an experimental database containing 38 CFFT beam specimens without internal reinforcing bars is compiled from the literature. The specimens are made of FRP tube surrounding a plain concrete core. At this stage, focus is on tubes with near-cross-ply laminates, which exhibit a near-linear behaviour. Future extension of the work will include CFFTs with angle-ply tubes, which exhibit considerable non-linear behaviour. The analytical procedure predicts the flexural capacities of the test specimens with an average test to prediction ratio of 1.13. A reliability analysis using the first order reliability method (FORM) is conducted and the reliability index values of 4.05 and 4.59 are found for under- and over-reinforced CFFTs, respectively, which are considered acceptable in light of reliability index values used in structural design codes, typically between 3.0 and 4.0.

1 INTRODUCTION

Hybrid structures using innovative systems such as concrete-filled fiber-reinforced polymer (FRP) tubes (CFFTs) are very effective in civil infrastructure applications. The corrosion-resistant FRP tube provides protection and confinement for the concrete core, thereby increasing its strength, ductility, and durability while simplifying construction as a stay-in-place form. Considerable research effort has been directed towards understanding and modelling the flexural behavior of CFFTs (Davol 1998, Burgueño 1999, Mirmiran et al. 2000, Fam and Rizkalla 2001). However, a broad statistical study is required to investigate uncertainty of variables and recommend resistance factors for design. In this paper, an analytical procedure is presented to compute flexural capacity of CFFTs with a comparison to an experimental database. The uncertainty of variables is estimated and then taken into account in a reliability analysis. Various material and geometrical parameters are considered as random variables and the effect of changes in these variables on the flexural capacity of CFFT members is established. Then, the reliability index is computed to evaluate the reliability of the analytical procedure and strength reduction factors for a representative case to establish the methodology to be used in a future comprehensive study that covers a wider design space.

2 FLEXURAL CAPACITY OF CFFTS

2.1 Flexural Failure of CFFTs

There are two typical modes of failure for a CFFT member in flexure. The first is a tension failure characterized by rupture of the tube on the tension side under longitudinal tensile stresses (i.e. a uniaxial state of stress). The second is a compression failure, which is not by concrete crushing as in conventional reinforced concrete members, but is triggered primarily by failure of the tube, immediately followed by crushing of concrete as a secondary failure. For CFFT flexural members it is predominantly governed by compression failure of the tube under longitudinal compressive stresses, where the hoop tensile stresses (i.e. confinement effect) is insignificant. It is to be noted that the concrete core in CFFT under flexure is assumed to be represented by an unconfined stress-strain curve in compression, with an extended strain softening that is limited by the tube ultimate longitudinal compressive strain. The mode of failure is identified by the FRP reinforcement ratio, ρ, which is the ratio of the cross-sectional area of the FRP tube to the cross-sectional area of the concrete core. In CFFT members in flexure, the balanced reinforcement ratio, ρ_b, is defined as the reinforcement ratio which results in tensile rupture and compressive crushing of the FRP tube under longitudinal stresses, simultaneously. As a result, there is a unique tube thickness that provides the balanced condition when the extreme tension and compression fibers of the FRP tube reach the ultimate tensile and compressive longitudinal strengths, simultaneously. Overall, ρ greater than ρ_b implies compression-initiated failure. The balanced reinforcement ratio ρ_b and the balanced tube thickness t_b are defined as follows:

[1] $$\rho_b = \frac{4t_b}{D}$$

[2] $$t_b = \frac{\alpha f_c' D}{4\pi(f_{tu} - f_{cu})}\left[2\theta - Sin(2\theta)\right]$$

where f_{tu} and f_{cu} are the ultimate tensile and compressive strengths of the FRP tube in the longitudinal direction, respectively; f_c' is the compressive strength of unconfined concrete; and D is the average diameter of the FRP tube; The angle θ in radian is corresponding to the neutral axis location; and parameters α and β are the equivalent stress block parameters for compressive concrete that are calculated as follows (AASHTO 2012):

[3] $$Cos\theta = 1 - 2\beta\frac{f_{cu}}{f_{tu} + f_{cu}}$$

[4] $$\alpha = 7.325\left(\frac{\varepsilon_{fcu}}{\varepsilon_c'}\right)^{-0.917} f_c'^{-1.086}$$

[5] $$\beta = 0.633\left(\frac{\varepsilon_{fcu}}{\varepsilon_c'}\right)^{0.247} f_c'^{0.222}$$

where f_c' is in ksi and ε_c' is the corresponding concrete strain at f_c'. Eqs 4 and 5 were established based on an equivalent concrete stress block with parameters α and β. These parameters were established for a large range of concrete compressive strengths of 3 to 15 ksi and ultimate longitudinal compressive strain of the FRP tube ranging from 2 to 10 times ε_c'. The two conditions used to establish α and β are: i) the area under the non-linear stress-strain curve is equal to the rectangular stress area, and ii) the location of the centroid of the area under the nonlinear curve is the same as that of the rectangular stress distribution. While this technique conventionally applies to rectangular sections, it is also adopted here for the circular section. Most design codes use the same α and β for any cross-section geometry.

2.2 Flexural Design Capacity

The CFFT is detailed, fabricated and constructed such that full composite action is achieved between the tube and concrete. Thus, it is assumed that perfect bond exists between concrete and the FRP tube. The longitudinal strains in the concrete vary linearly over the depth of the member and are proportional to the distance from the neutral axis. Additionally, the following assumptions are adopted:

i) FRP tube is strong enough to contribute longitudinally in compression;
ii) concrete is partially confined when circular tubes are used. So, the FRP tube controls failure, whether in tension or compression. As such, the concrete longitudinal compressive strain at failure may exceed 0.003;
iii) tension failure is defined by tensile rupture of the FRP tube under uniaxial longitudinal stresses, while compression failure is defined by crushing of the FRP tube under uniaxial longitudinal stresses. Confinement in flexure is not significant enough to weaken the tube under longitudinal compression or longitudinal tension;
iv) concrete stress-strain relationship proposed by Popovics (1973), with an extended strain softening beyond the usual strain of 0.003 is used to obtain the moment capacity based on equilibrium and strain compatibility; and
v) stress-strain relationships of the FRP tube in tension and compression is taken as linear elastic and the tensile strength of the concrete is neglected.

Based on the assumptions, the flexural design capacity M_r of a CFFT section is defined as Eq. 6, in which M_n is the nominal moment capacity.

[6] $M_r = \varphi M_n$

The resistance factor, ϕ, for flexure is primarily taken as Eq. 7. The resistance factors primarily taken here are essentially the same as those used in FRP-reinforced concrete structures governed by FRP rupture for tension failure and classic concrete crushing for compression failure. As noted earlier, the compression failure of CFFT members is different. Later in this paper, a reliability analysis is carried out to refine the resistance factors.

[7a] $\phi = 0.55 \quad \text{if } \rho \le \rho_b$

[7b] $\phi = 0.3 + 0.25\dfrac{\rho}{\rho_b} \quad \text{if } \rho_b \le \rho \le 1.4\rho_b$

[7c] $\phi = 0.65 \quad \text{if } \rho \ge 1.4\rho_b$

The nominal moment capacity M_n is determined either by the general method or the simplified method as follows (AASHTO 2012). In the general method, the nominal moment capacity M_n is calculated based on a rigorous cross-sectional analysis that satisfies equilibrium and strain compatibility, and utilizes appropriate material constitutive relationships for the concrete and FRP, and failure modes, satisfying the aforementioned assumptions. The simplified method proposed by Fam and Son (2008) is applicable only for tension-controlled failure of the circular CFFT members (i.e. $\rho \le \rho_b$). In this case, in lieu of the rigorous equilibrium and strain compatibility approach, M_n can be calculated as follows:

[8] $M_n = 0.0045 D_o^3 f_c' \left(100\dfrac{4t}{D_o}\dfrac{f_{tu}}{f_c'}\right)^{0.815}$

where t is the structural wall thickness of the tube, D_o is the outer diameter, f_{tu} is the design tensile strength of FRP laminate in longitudinal direction, and f_c' is the concrete unconfined compressive strength. Equation 8 is an empirical formula developed through best fitting of experimental data and finite element model results of a parametric study. Both the experimental and numerical data covered a wide range of CFFT geometric and mechanical properties.

3 EXPERIMENTAL DATABASE

To assess the reliability of the design procedure, a database containing the test results of 38 CFFT specimens in flexure was compiled from the literature, as shown in Table 1. The specimens considered in the analysis are only those made of a circular FRP tube with fibers oriented close to the axial and hoop direction of the tube (i.e. near-cross-ply tubes).

Table 1: Experimental database of circular CFFTs made of cross-ply tubes and plain concrete in flexure

Specimen #	Reference of test data	D_o (mm)	t (mm)	f_c' (MPa)	$M_{u, test}$ (kN.m)	Failure	$M_{n, General. model}$ (kN.m)	Failure	Test to Predict Ratio	$M_{n, Simplified. model}$ (kN.m)	Test to Predict Ration	ρ (%)	ρ_b (%)
1	Fam (2000) and Fam and Rizkalla (2002)	100	3.1	38	14.1	T	6.3	C	2.26	NA	NA	12.32	2.50
2		168	2.6	58	19.5	T	19.3	T	1.01	19.6	0.99	6.10	27.14
3		89	2.1	38	4.0	T	2.9	T	1.39	3.0	1.37	9.21	9.79
4		326	6.4	60	157.7	T	205.2	T	0.77	208.9	0.75	7.85	21.44
5		326	6.4	60	157.0	T	205.2	T	0.76	208.9	0.75	7.85	21.44
6		320	6.0	67	125.7	T	121.1	T	1.04	127.4	0.99	7.45	15.98
7		320	6.0	67	123.8	T	121.1	T	1.02	127.4	0.97	7.45	15.98
8		626	5.4	33	467.0	T	446.3	T	1.05	446.3	1.05	3.46	11.22
9		626	5.4	33	506.0	T	446.3	T	1.13	446.3	1.13	3.46	11.22
10		942	8.9	58	1681.0	T	1745.6	T	0.96	1820.5	0.92	3.79	14.90
11		942	8.9	58	1632.0	T	1745.6	T	0.93	1820.5	0.90	3.79	14.90
12	Fam et al. (2003a)	625	5.4	33	499.6	T	455.3	T	1.10	445.5	1.12	3.46	11.28
13		625	5.4	33	525.9	T	455.3	T	1.16	445.5	1.18	3.46	11.28
14	Fam et al. (2003b)	326	6.4	60	163.0	T	206.1	T	0.79	210.2	0.78	7.85	20.39
15		320	6.0	67	132.0	T	121.1	T	1.09	127.3	1.04	7.45	15.94
16	Mirmiran et al. (2000)	348	9.6	26	467.3	C	358.6	C	1.30	NA	NA	11.03	10.19
17	Naguib et al. (2002)	152	16	38	111.4	T	110.6	T	1.01	100.3	1.11	42.11	30.49
18	Davol (1998)	362	9.7	21	660.0	C	603.8	C	1.09	NA	NA	10.65	0.95
19		361	8.9	31	720.0	C	715.9	C	1.01	NA	NA	9.86	2.64
20		157	2.3	46	44.3	C	41.5	C	1.07	NA	NA	5.87	1.18
21		161	4.6	46	102.0	C	107.1	C	0.95	NA	NA	11.41	2.70
22	Lee et al. (2002)	179	6.7	40	75.0	T	83.6	T	0.90	78.9	0.95	15.01	3.65
23		179	6.7	40	74.0	T	83.6	T	0.89	78.9	0.94	15.01	3.65
24	Qasrawi and Fam (2008)	330	5.3	63	180.0	T	140.8	T	1.28	145.5	1.24	6.42	37.44
25	Helmi et al. (2005)	367	4.8	59	198.0	T	239.1	T	0.83	241.5	0.82	5.23	17.83
26	Mitchell and Fam (2010)	220	4.2	45	56.5	T	43.4	T	1.30	43.8	1.29	7.55	33.45
27		220	4.2	45	55.2	T	43.4	T	1.27	43.8	1.26	7.55	33.45
28		220	4.2	45	57.3	T	43.4	T	1.32	43.8	1.31	7.55	33.45
29	Sadeghian et al. (2010)	169	3.5	38	21.4	T	17.0	T	1.26	17.1	1.25	8.28	40.80
30		169	3.5	38	22.7	T	17.0	T	1.34	17.1	1.32	8.28	40.80
31		169	3.5	38	19.8	T	17.0	T	1.17	17.1	1.15	8.28	40.80
32	Zakaib (2013)	219	4.3	41	50.8	T	44.6	T	1.14	45.1	1.13	7.85	29.27
33		219	4.3	30	59.4	T	42.3	T	1.41	42.5	1.40	7.85	25.10
34		219	4.3	36	49.4	T	43.7	T	1.13	44.0	1.12	7.85	27.46
35		219	4.3	30	52.1	T	42.3	T	1.23	42.5	1.22	7.85	25.10
36		169	3.6	37	22.5	T	19.1	T	1.18	19.8	1.13	8.40	24.07
37		169	5.2	37	26.6	T	22.6	T	1.18	23.6	1.13	12.28	32.99
38		114	4.0	37	11.2	T	9.9	T	1.13	10.1	1.10	14.07	26.64
	Average	310	5.6	44	245.9	-	241.9	-	1.13	234.8	1.09	8.98	19.72

T: tension failure of tube; C: compression failure of tube; NA: not available as simplified model was set for tension failure only

In Table 1, the concrete fill is solid without any reinforcing bars. Specimens with angle-ply tubes (Ahmed et al. 2008, Zhu et al. 2006, Chabib et al. 2005) were excluded from the database as their performance is quite different from cross-ply tubes. Also, CFFT specimens with internal reinforcing bars (Mohamed and Masmoudi 2010) were excluded. Using the general method, the nominal moment capacity of each CFFT specimen was computed and compared to the experimental moment capacity. Also, the reinforcement ratio of each specimen was calculated and compared to the balanced reinforcement ratio, for use in the reliability analysis. Overall, Table 1 shows that the general and simplified models predict the moment capacities are close with an average test to prediction ratio of 1.13 and 1.09, respectively. The simplified model is only applicable for the specimens with tension failure.

4 RELIABILITY ANALYSIS

A First Order Reliability Method (FORM) analysis (Nowak and Collins 2000) was conducted to assess the reliability index, β, for a typical CFFT case from the experimental database. Load, material, and geometric statistical models were extracted from the literature and are listed in Table 2. Figure 1 shows randomly generated variables for material and dimensions of Specimen #8 of the database

Table 2: Statistical characteristics of considered random variables

Variable		**Bias**	**COV (%)**	**Distribution**	**Reference**
Materials	FRP, f_{tu}	1.10	8.3	Weibull (Ex. Typ. III)	Okeil et al. (2013)
	Concrete, $f_c^{'}$	1.17	10.0	Lognormal	Nowak and Szerszen (2003)
Dimensions	Diameter, D_o	1.00	1.0	Normal	Okeil et al. (2013)*
	Thickness, t	1.00	2.0	Normal	Okeil et al. (2013)*
Loads	Dead, ζ_D	1.05	10.0	Normal	Szerszen and Nowak (2003)
	Live, ζ_L	1.00	18.0	Extreme Type I	Szerszen and Nowak (2003)

* by analogy from similar studies.

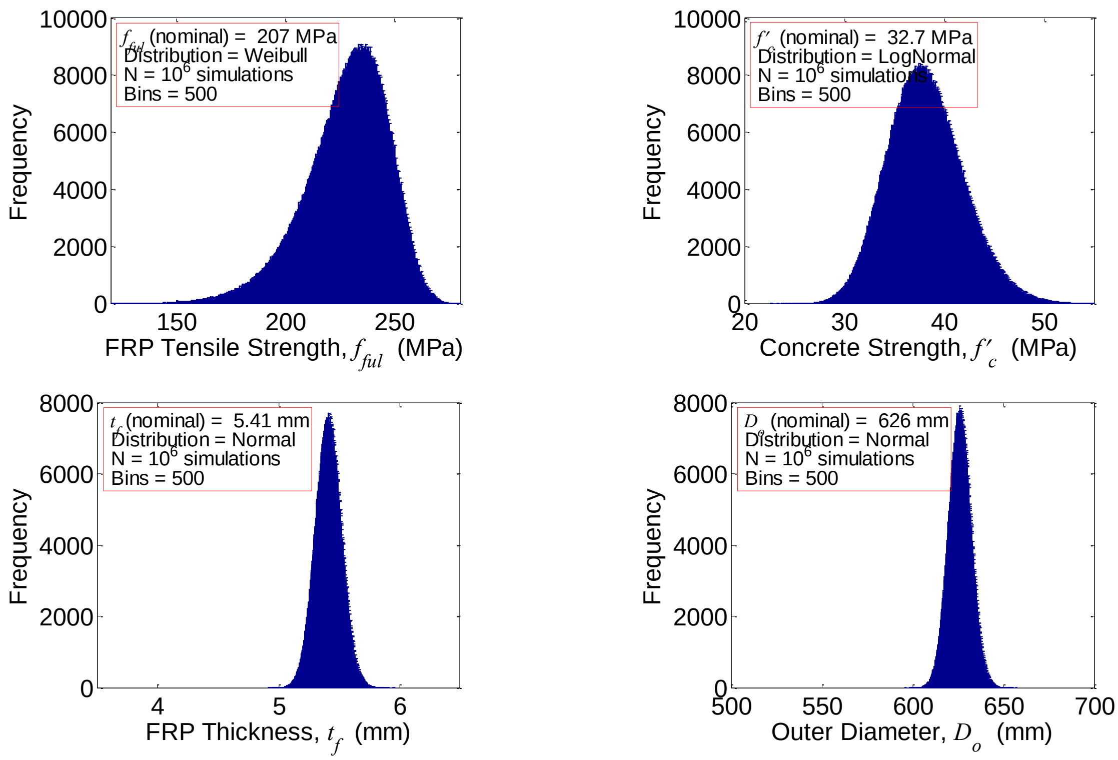

Figure 1: Randomly generated variables for material and dimensions of Specimen #8 of the database

The resistance model, *R,* which takes into account uncertainties due to material (M), fabrication (F), and model accuracy (P), had to be established for the proposed design equations. Monte Carlo simulations were run to obtain randomly generated properties for three representative scenarios that were chosen to cover a wide range of CFFT applications, which were then inserted into the proposed model to assess the model uncertainties due to material variability and fabrication tolerances. The three cases were selected from the database (Table 1) to include a small (#38), medium (#25), and large (#8) diameter CFFT cases. The obtained results for Specimen #8 are shown in Figure 1 for one million simulations. The combined effect of these two sources of uncertainty results in a coefficient of variation, *COV(MF)*=7.7% regardless of the size. The bias (λ_{MF}), however, was slightly affected by the CFFT size and ranged between 1.089 and 1.11. An average value of 1.10 was used in subsequent FORM analyses. Figure 2 shows the resulting distribution for Specimen #8's resistance due to material and fabrication uncertainties, which was found to be best modelled using a normal distribution based on goodness-of-fit tests.

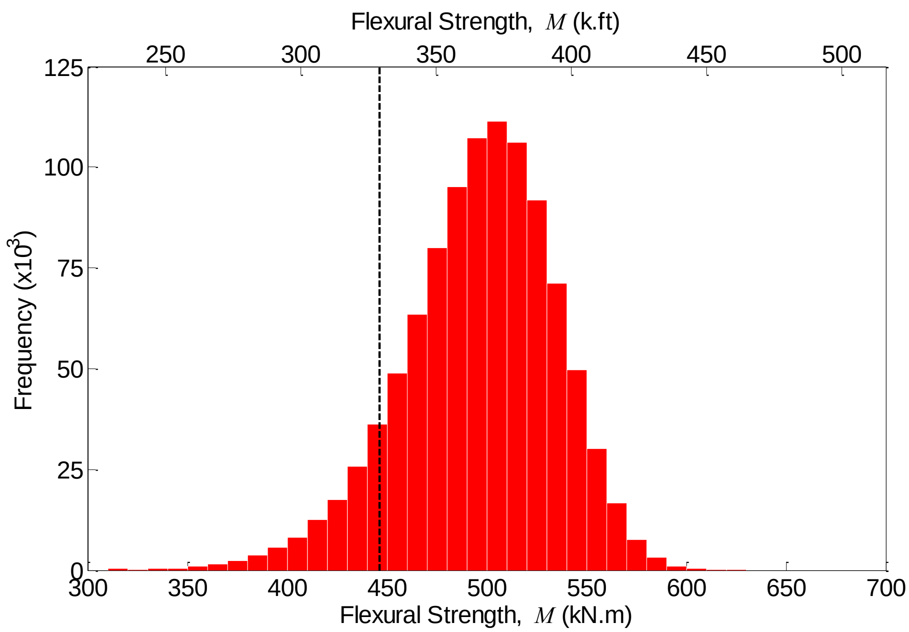

Figure 2: Effect of material and fabrication uncertainties on resistance model for Specimen #8 of the database

Model accuracy, *P*, in predicting CFFT flexural resistance, was assessed by comparing experimental results from the database with model predictions. The comparison revealed that this source of uncertainty was different for CFFT specimens with $\rho \le \rho_b$ than for specimens with $\rho \ge 1.4\rho_b$. This classification grouped the specimens in the database into 29 for the former and 6 for the latter. Three specimens were excluded from the database because of a discrepancy between the predicted and observed mode of failure. Excluding these specimens is considered acceptable since it affects the analysis conservatively as the model under-predicted their strength. The database did not include specimens with $\rho_b \le \rho \le 1.4\rho_b$. The bias and coefficient of variation for the model accuracy were calculated to be λ_P=1.11 and *COV(P)*=16.1% for specimens with $\rho \le \rho_b$ and λ_P=0.983 and *COV(P)*=8.8% for specimens with $\rho \ge 1.4\rho_b$. A normal distribution was assumed for model uncertainties (P).

The reliability index β was evaluated for the strength limit state using the following limit state function:

[9] $g = \alpha_{MF}\xi_P M_n - \zeta_D D_n - \zeta_L L_n$

in which the nominal values for the resistance M_n, and the dead and live load demands, D_n and L_n are used as the basis for the random variable representing their effect. The random variables are obtained using the statistical characteristics described earlier for material and fabrication uncertainties α_{MF}, model accuracy ξ_P, and dead and live loads ζ_D and ζ_L; respectively. It should be noted that an iterative algorithm was used to find the solution of Eq. 9; i.e., β, where equivalent normally distributed random variables in the reduced space (standard forms of the random variables) were determined for each non-normal random variable during each iteration (Nowak and Collins 2000). From the FORM analyses, it was revealed that the reliability index β, for CFFTs with $\rho \leq \rho_b$ is equal to 4.05, whereas a β value equal to 4.59 was obtained for CFFTs with $\rho \geq 1.4\rho_b$. Both values are considered acceptable in comparison with target reliability index values used in structural design codes, which typically range between 3.0 and 4.0. This implies that there may be room for increasing the resistance factor primarily used in this study once a complete reliability investigation is conducted. It should be noted that in determining the material and fabrication uncertainties, the simplified model (Eq. 8) was used. However, the more accurate general model was used for assessing the model accuracy *P*. As the predictions using both simplified model and general model are very close (see Table 1), this approximation was deemed acceptable for this study. Both models will be considered in two separate studies when this reliability study will be completed.

5 CONCLUSIONS

In this paper, an analytical procedure was presented to compute flexural capacity of CFFTs for bridge applications. The specimens with angle-ply tubes were excluded from the study at this stage due to a very different flexural behavior. The procedure was verified against an experimental database containing 38 specimens resulting in an average test to prediction ratio of 1.13. Then, a statistical resistance model was developed to determine the bias and coefficient of variation due to material, fabrication and model uncertainties. Three CFFT sizes were considered for assessing the effect of material and fabrication uncertainties, which resulted in a bias of 1.10 and a coefficient of variation of 7.7%. Additional uncertainties due to model accuracy were also determined for tension and compression modes of failure. A FORM reliability analysis was conducted using the obtained resistance model to assess the reliability index using current resistance factor equations. The following conclusions can be drawn:

- It was revealed that the reliability index β, for CFFTs with $\rho \leq \rho_b$ is equal to 4.05, whereas a β equal to 4.59 was obtained for CFFTs with $\rho \geq 1.4\rho_b$. Both values are considered acceptable in comparison with target reliability index values used in structural design codes, which typically range between 3.0 and 4.0.
- The current resistance factor, ϕ, equations (Eq. 7) produce designs that meet code reliability targets.
- The presented reliability study was based on a limited experimental database, especially for specimens with $\rho \geq 1.4\rho_b$. A larger database of experimental results would allow for better assessment of uncertainties due to model accuracy over a wider design space.

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