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FRP-Confined Non-Circular Reinforced Concrete Columns: Assessment of International Guidelines

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ABSTRACT: Axial capacity enhancement of reinforced (RC) columns by means of fiber reinforced polymer (FRP) confinement is a strengthening technique that has become widely popular in the last fifteen years. In the past few years, an extensive amount of analytical and experimental research has been conducted on FRP confined columns, although mainly on small scale (often un-reinforced) specimens. Full-scale test data are scarce, mostly due to limitations of test equipment. As such, most of the analytical models published to date are based on small-scale testing and incorporate limitations on the applicability of FRP confinement to large scale columns - in particular to columns with rectangular cross-sections.

This paper presents the results of recent tests performed on full-scale FRP confined rectangular columns subject to pure axial compressive load. Additional test data available in the literature for full scale column tests are also presented.

The experimental database was used to compare the predicted column strength using four international guidelines for FRP confinement: ACI 440.2R-2008 by the American Concrete Institute (USA), the Technical Report 55-2004 by the Concrete Society (UK), Bulletin 14-2001 by fib - fédération internationale du béton (Switzerland), and CNR-DT 204-2006 by the National Research Council (Italy).

1 INTRODUCTION

The confinement of reinforced concrete (RC) columns by means of fiber reinforced polymers (FRP) jackets is a technique used with growing frequency to increase the axial load carrying capacity and/or ductility of these compression members. The need for improved axial strength can result from one or more of the following: (a) lower concrete compressive strength than the design strength; (b) errors in design and/or construction; (c) poor detailing in either the transverse reinforcement or longitudinal reinforcement; (d) deterioration of internal steel reinforcement due to chemical/environmental effects; (e) design code update; (f) increase in loading demand due to changes or additions to the structure; (g) blast and/or impact loading upgrade; and (h) extension of service life.

The strengthening of RC columns by means of FRP jackets is based on the basic material behavior concept that lateral confinement of concrete can increase its axial compressive strength and ductility. Typically, strength enhancement is obtained by applying confinement over the entire height of the member. Ductility can be achieved by confining the top and bottom ends of a column, which are the regions where flexural plastic hinges will potentially form. Improving ductility stems from the need for energy dissipation which allows for improved plastic deformation of the element and, ultimately, of the structure. Ductility enhancement is typically required in existing columns that are subjected to a combination of axial load and bending moment because of a change in code or a correction for design or construction errors. When an axial compressive strength increase is required, the main controlling factor that defines applicable strengthening techniques is the required level of strength increase. The enhanced strength typically has been achieved using steel jacketing, section enlargement, or FRP wrapping.

Several studies have been conducted on RC columns of non-circular cross-sections; however, the majority of these studies primarily were performed on small specimens of plain concrete due to the high cost and lack of high-capacity testing equipment. Several confinement models for rectangular columns have been proposed (Lam and Teng 2003) that have become the basis for current design provisions. However, the predictive equations found in some the current design guides are mostly based on approaches developed for circular columns and then modified by a "shape factor" or "efficiency factor" that accounts for the rectangular shape of the column.

The objective of this study is to evaluate the axial strength prediction accuracy of four international FRP guidelines for FRP-confined rectangular columns. This is accomplished by comparing the full-scale experimental results with predicted axial strengths. Conclusions are made regarding the accuracy of the guidelines utilized and the need for additional research.

2 DESIGN GUIDELINES

Much of the research conducted in the past twenty years has become the basis for the currently available international design guides for FRP strengthening. The most commonly used of these guidelines include: "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures" by the American Concrete Institute (ACI Committee 440.2R-08 2008), "Design Guidance for Strengthening Concrete Structures Using Fibre Composite Material" Technical Report 55 by the Concrete Society (TR 55 2004), "Externally Bonded FRP Reinforcement for RC Structures" Technical Report by the fédération internationale du béton (fib Bulletin 14 2001), and "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures" by the Italian National Research Council (CNR-DT 200-2004).

The design philosophies adopted by these guidelines for the design of RC members strengthened with FRP are based on limit state principles. While all guidelines have a consistent approach to the use of load amplification factors, strength reduction factors are addressed in two different ways. For ACI, the strength reduction factors ϕ (typically with values less than 1.0) are applied to the computed overall nominal capacity, and are internal force dependant (flexure, shear, or axial force). For the Concrete Society, fib, and CNR, material safety factors γ are applied individually to each material (concrete, steel reinforcement, and FRP). These material safety factors are typically larger than 1.0 and are used as dividers.

For the case of FRP materials, ACI considers an environmental factor that is a function of the type of FRP and exposure conditions, and an additional strength reduction factor (ψ_f) that applies to the strength contribution of FRP. The Concrete Society recommends using FRP material safety factors based on strain and modulus of elasticity, as well as a reduction factor that is a function of the type of FRP system and method of application. Guidelines set forth by the fib only consider a FRP material safety factor based on the type of material, while CNR considers a material safety factor based on the failure mode, an environmental factor, and an additional strength reduction factor for FRP confinement. Table 1 shows the reduction factors and material safety factors used by the different guidelines. In Table 1, the subscripts "c," "s," and "f" refer to concrete, reinforcing steel, and FRP, respectively.

For rectangular column confinement with FRP, ACI and CNR set a maximum allowable column section aspect-ratio equal to 2.0. The Concrete Society specifies a maximum section aspect-ratio of 1.5. These guides state that the confining effects of FRP for cases beyond these limits should be neglected unless demonstrated by experimental evidence. When it comes to section dimensions, ACI and CNR set an upper limit of column section to 900 mm while the Concrete Society limits the larger dimension to 200 mm. The fib does not set any limits, neither on the maximum dimension the column cross-section, nor on the maximum section aspect-ratio.

Table 2 presents a synopsis of the expressions provided by each guideline for the calculation of the effective confinement pressure (f_l), the maximum compressive strength (f'_{cc}), and the ultimate axial strain (ε_{ccu}) for the cases of FRP-confined RC columns of non-circular cross-sections. All of the guidelines consider the generally accepted approach of an effectively confined sectional area defined by four second-degree parabolas with initial slopes of diagonal lines between the corners. Because they are based on the model by Lam and Teng (2003) with few slight variations, the models from ACI and Concrete Society are very similar. The expressions in the fib guideline were developed by Spoelstra and Monti (1999) based on regression analysis from their own proposed model results. The CNR guideline does not provide any reference model for its provisions.

3 EXPERIMENTAL TESTS

The experimental evaluation consisted of testing real-size RC rectangular columns confined with carbon FRP and subjected to pure axial compressive loading. The test matrix included 22 specimens, divided into six series of three specimens each and two series of two specimens (Rocca 2007). Of the 22 test columns, 19 had rectangular cross-section. The largest column tested had a cross-sectional area of 0.8 m^2 and the smallest one had an area of 0.1 m^2. Test objectives included investigating the effect of different variables, such as the geometry of the specimen (circular, square, and rectangular), cross-sectional area, the side aspect-ratio, and a height-to-width aspect ratio. Results on the non-circular specimens along with collected similar data available in the literature are used in this study to evaluate the four selected guidelines.

Table 1 - Strength Reduction and Material Safety Factors for Different Guidelines

Guideline	Strength Reduction Factors	Materials Safety Factors	FRP Additional Factors
ACI	ϕ = 0.65 (ties)	Not Applicable	ψ_f = 0.95 C_E = environmental reduction factor = 0.95 for CFRP, 0.75 for GFRP and interior exposure
Concrete Society	Not Applicable	γ_c = 1.50 γ_s = 1.05 γ_ε = partial safety factor for FRP strain = 1.25 CFRP), 1.95 (GFRP) γ_E = partial safety factor for FRP modulus = 1.1 (CFRP), 1.8 (GFRP)	γ_{mm} = function of the type of system and method of application. For sheets applied by wet lay-up the recommended value is 1.2
fib	Not Applicable	γ_c = 1.50 γ_s = 1.15 γ_f = 1.2 (CFRP), 1.3 (GFRP)	Not Applicable
CNR	Not Applicable	γ_f = 1.1 (corresponding to FRP rupture) $\gamma_{R,d}$ = 1.1 (partial factor for resistance, for confinement)	η_a = environmental reduction factor = 0.95 for CFRP, 0.75 for GFRP

Table 2 - Summary of Design Guideline Models for Non-Circular Cross-Sections

Guideline	Effective Confinement Pressure f_l (MPa)	Confined Concrete Compressive Strength for Purpose of Design f'_{cc} (MPa) and Ultimate Axial Compressive Strain of Confined Concrete ε_{ccu}
ACI	$f_l = \frac{2nt_f E_f \varepsilon_{fe}}{\sqrt{b^2+h^2}}$ $\varepsilon_{fe} = 0.55\varepsilon_{fu}$	$f'_{cc} = f'_c + \psi_f 3.3\kappa_s f_l$; $\kappa_s = (A_e/A_c)(b/h)^2$ $\frac{A_e}{A_c} = \left(1 - \frac{((b/h)(h-2r)^2 + (h/b)(b-2r)^2)}{3bh} - \rho_l\right) \Big/ (1-\rho_l)$ Confinement effectiveness ratio: $f_l / f'_c > 0.08$ $\varepsilon_{ccu} = \varepsilon'_c\left(1.5 + 12\kappa_b \frac{f_l}{f'_c}\left(\frac{\varepsilon_{fe}}{\varepsilon'_c}\right)^{0.45}\right) \le 0.01$; $\kappa_b = (A_e/A_c)(h/b)^{0.5}$
Concrete Society	$f_l = \frac{2nt_f E_f \varepsilon_{fe}}{\sqrt{b^2+h^2}}$	$f'_{cc} = f'_c + 2k_s f_l$; $k_s = (A_e/A_c)(b/h)$; $l_{ol} = \sqrt{\frac{(h-2r)^2}{4} - \frac{b(h-2r)}{2}}$ = length of overlapping region of parabolas defining effective confined area in cross-section $\frac{A_e}{A_c} = \left(1 - \frac{((h-2r)^2 + (b-2r)^2) - 3A_{ol}}{3bh} - \rho_l\right) \Big/ (1-\rho_l)$ $A_{ol} = \begin{cases} 0 \rightarrow 2b \ge (h-2r) \\ \frac{4(l_{ol})^3}{3(h-2r)} + l_{ol}(2b - (h-2r)) \rightarrow otherwise \end{cases}$ = area of overlapping region No expressions for ε_{ccu} are provided.
fib	f_l = Minimum of $f_{l,x}$ and $f_{l,y}$ $f_{l,x} = \rho_{fx} k_s E_f \varepsilon_{fu}$ $f_{l,y} = \rho_{fy} k_s E_f \varepsilon_{fu}$	"Practical" formulas: $f'_{cc} = f'_c\left(0.2 + 3\sqrt{\frac{f_l}{f'_c}}\right)$; $k_s = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-\rho_l)}$ $\varepsilon_{ccu} = \varepsilon'_c\left(2 + 1.25\frac{E_c}{f'_c}\varepsilon_{fu}\sqrt{\frac{f_l}{f'_c}}\right)$
CNR	$f_l = k_s \frac{1}{2}\rho_f E_f \varepsilon_{fe}$ $\varepsilon_{fe} = \min(\varepsilon_{fu}, 0.004)$	$f'_{cc} = f'_c\left(1 + 2.6\left(\frac{f_l}{f'_c}\right)^{2/3}\right)$; $k_s = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh}$ Confinement effectiveness ratio: $f_l / f'_c > 0.05$ No expressions for ε_{ccu} are provided

4 EXPERIMENTAL DATABASE

Specimens with the following features were included in the database presented in Table 3: at least one of the dimensions on the cross-section is 300 mm, side aspect-ratios (h/b) not greater than 2.0, and FRP jackets (full coverage) with the fibers oriented perpendicular to the axis of the column. Table 3 is composed of 39 specimens (15 control and 24 FRP-wrapped) from six different research studies. Out of the 24 strengthened specimens, 14 had square cross-section, and 10 had rectangular.

Three types of FRP material were used in the specimens in the database: Carbon (CFRP), Glass (GFRP), and a Hybrid Glass-Basalt (HFRP). The specimens' designation corresponds to the authors, as follows: "KE" to Kestner et al. (1997), "WR" to Wang and Restrepo (2001), "YO" to Youssef (2003), "CH" to Carey and Harries (2003), "RO" to Rocca (2007), and "DL" to De Luca (2009). The last letter in each specimen designation refers to whether the specimen is square (S) or rectangular (R) in shape. The data is presented in terms of following parameters: side dimensions (b, h), section aspect-ratio (h/b), column height (H), corner radius (r), type of FRP used, FRP mechanical properties (E_f, ε_{fu}), nominal ply thickness of FRP (t_f), FRP volumetric ratio (ρ_f), yield strength (f_y), ratio of longitudinal steel reinforcement (ρ_l), unconfined concrete compressive strength (f'_c), maximum compressive load (P_{max}), and ratio of normalized maximum concrete axial stress of strengthened specimen to corresponding control unit ($(\sigma_c/f'_c)_{FRP}/(\sigma_c/f'_c)_{control}$)). The maximum concrete axial stress σc is computed as follows: $(P_{max} - As \times f_y)/Ac$; where As is the total area of longitudinal steel reinforcement, and Ac is the cross-sectional area of concrete.

5 COMPARISON OF EXPERIMENTAL AND PREDICTED STRENGTHS

The experimental results presented in Table 3 are compared with the predictions of the four international design guides in terms of the increase in the amount of concrete compressive strength. The comparison is made by plotting the experimental versus the predicted values, with a 45-degree line having a ±5% error band. Data-points falling below the error band are considered unconservative or overestimated by the guideline, whereas points above the band are considered conservative.

ACI and CNR guidelines specify minimum confinement ratios (f_l/f'_c) of 0.08 and 0.05, respectively. Therefore, not all the 24 specimens can be used for the evaluation of these two guidelines. Even though the Concrete Society limits the applicability of its model to columns with a maximum side dimension of 200 mm and section aspect-ratio of 1.5, all the specimens were considered. Figure 1 illustrates the results of concrete compressive strength comparisons. In general, all the guidelines show a certain degree of scattering in the data - in particular fib and CNR.

Predictions by ACI (Figure 1(a)) show three data-points that appear to be overestimated: CH2_S, DL3_S, and DL3b_R. However, the first two specimens were reported to fail prematurely with no clear justification by the authors (Carey and Harries 2003). For DL3b_R, the P_{max} reached by this specimen was slightly lower than that of the unconfined specimen. This "premature" failure could have been due to eccentricity of the applied load or an error during the test (De Luca, 2009).

Although ACI and the Concrete Society provisions are based on the same model (with slight variations), the latter shows a few more data-points falling on the unconservative side of the plot (Figure 1(b)). The determination of the effective confinement pressure seems to be what creates the discrepancy: ACI includes a limitation on the effective strain of the FRP as opposed to the Concrete Society; the shape factor (k_s) in ACI 440.2R is determined as the product of the ratio A_e/A_c (which includes the section aspect-ratio) and the coefficient $(b/h)^2$ that reflects the effect of the section aspect-ratio on the effectively confined area. In addition, ACI 440.2R imposes a limit on the maximum compressive strain ($\varepsilon_{ccu} < 0.01$). The effect of this limit is apparent for specimen DL4b_R, in which the confined concrete strength f'_{cc} per ACI is 63 MPa with a value of $\varepsilon_{ccu} > 0.01$; the value of f'_{cc} is therefore recalculated using equations in ACI 440.2R, yielding a value of f'_{cc} = 57 MPa. The value provided the Concrete Society of 68.5 MPa, is unconservative.

Figure 1(c) shows the predictions according to fib. The scattering of this data may be due to the fact that the guideline imposes no reduction factor on FRP; no minimum confinement ratio (f_l/f'_c) is provided; no consideration is given for the effect of the section aspect-ratio; and the formulas for f'_{cc} and ε_{ccu} were determined by regression analysis considering only small cylinders.

Figure 1(d) presents the results by CNR, which basically shows all the data-points to be overestimated. This guideline recommends a limit on the effective FRP strain, and a minimum f_l/f'_c; however, the shape factor k_s does not incorporate the section aspect-ratio and the effect of longitudinal reinforcement. Unfortunately, the guideline does not provide a reference for the model adopted, and the authors could not further investigate the cause of this outcome.

For ACI, 14 of the 19 specimens (74%) show good agreement and are within ±5% of the experimental results. For the Concrete Society, 15 out of 24 specimens (63%) show good agreement and are within ±5% of the experimental results. Predictions by fib and CNR are more dispersed and tend to be unconservative. Figure 2 shows the ratio of design to experimental capacities of the specimens ($\phi P_{Theo}/P_{Exp}$). The design values were computed considering the material safety factors and/or the strength reduction factors as required by each guideline (see Table 1). Most of the predictions appear to be conservative with the exception of four cases by fib.

6 CONCLUSIONS

Design approaches for FRP confinement of RC columns of non-circular cross-sections from four international design guidelines were presented and compared to 24 full-scale experimental test results in terms of increase in concrete compressive strength and load carrying capacity.

In general, none of the guidelines provisions shows to be completely accurate in representing the axial strength increase for all of the experimental cases considered. This could be due to the manner in which effective confinement pressure is estimated by each guideline. Only ACI and CNR consider a reduction on the effective strain of the FRP. CNR and fib provide an expression that does not include the effect of the section aspect-ratio on the effectively confined area, as opposed to ACI and the Concrete Society. It was also noted the limit on ε_{ccu} to 0.01, as recommended by ACI, is reasonable to prevent excessive cracking and loss of concrete integrity. The predictions by ACI and the Concrete Society better estimate of the nominal axial strength.

For ACI, 14 of the 19 specimens considered (74%) show good agreement and are within ±5% of the experimental results. For the Concrete Society, 15 out of 24 specimens considered (63%) show good agreement and are within ±5% of the experimental results. Predictions by fib and CNR are more dispersed and tend to be unconservative.

Data on real-size RC columns of non-circular section is still scarce, but when more experimental and analytical work becomes available, it will be possible to further verify the precision of available design guides and develop more accurate design models.

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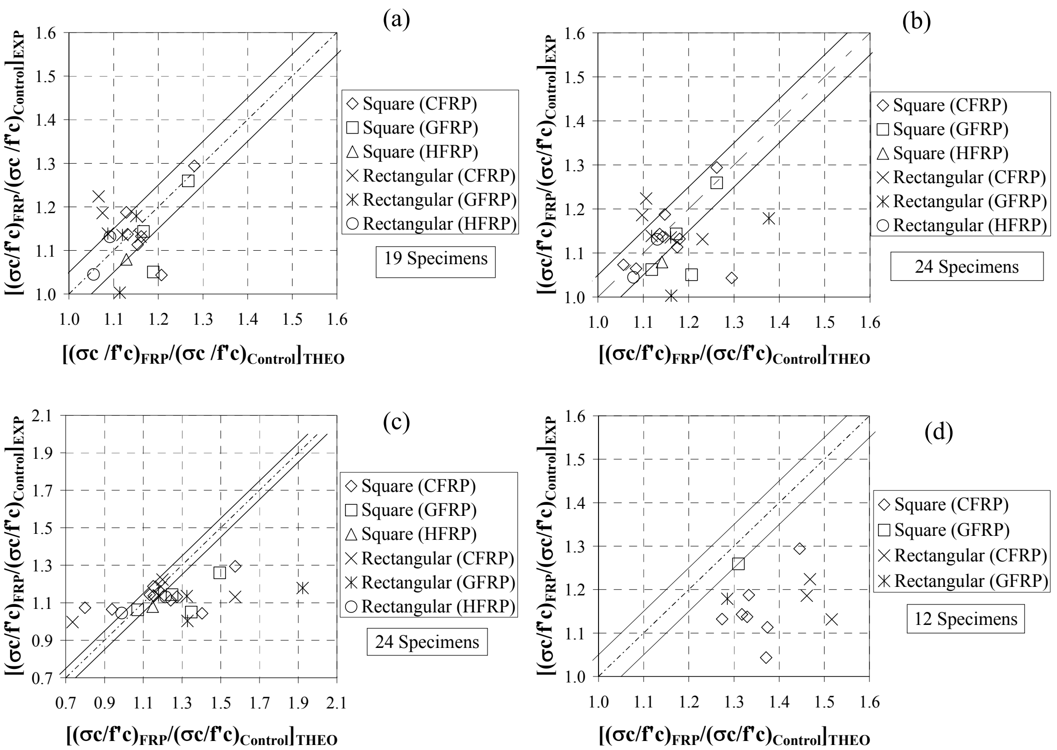

Figure 1 - Performance of Guidelines: (a) ACI 440.2R-08; (b) Concrete Society (TR 55); (c) fib (Bulletin 14); (d) CNR-DT 200/2004

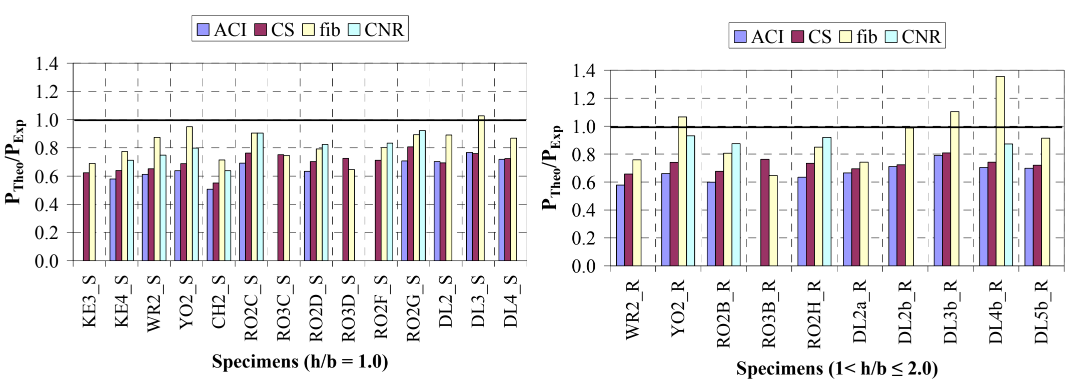

Figure 2 - Guidelines Performance – Ratio of Design Axial Load Capacity to Experimental – Square (h/b = 1) and Rectangular (1 < h/b ≤ 2) Sections

Table 3 - Experimental Database

Specimen Code	Geometry					FRP Material Characteristics					Long. Steel Reinforcement		f'_c (MPa)	P_{FRP} (kN)	$(\sigma_c/f'_c)/(\sigma_c/f'_c)_{control}$
	b (mm)	h (mm)	h/b	H (mm)	r (mm)	Type	E_f (GPa)	ε_{fu} (%)	t_{ply} (mm)	ρ_f (%)	f_y (MPa)	ρ_l (%)			
KE3_S	457	457	1.0	1830	38	GFRP	25	1.90	0.864	2.27	457	1.48	31.50	8270	1.06
KE4_S	457	457	1.0	1830	38	CFRP	231	1.50	0.165	0.43	457	1.48	31.50	8720	1.13
WR2_S	300	300	1.0	900	30	GFRP	20.5	2.00	1.270	3.39	439	1.5	18.90	2525	1.26
WR2_R	300	450	1.5	900	30	GFRP	20.5	2.00	1.270	2.82	439	1.5	18.90	3598	1.14
YO2_S	381	381	1.0	762	38	CFRP	104	1.25	0.584	2.45	414	1.60	41.22	7440	1.29
YO2_R	254	381	1.5	762	38	CFRP	104	1.25	0.584	3.07	414	1.60	41.07	4403	1.13
CH2_S	540	540	1.0	1630	51	CFRP	72.5	1.21	1.000	2.22	414	1.41	33.50	14738	1.04
$RO2_B$_R	318	635	2.0	1372	30	CFRP	291	0.93	0.167	1.10	447	1.56	30.41	7449	1.22
$RO3_B$_R	318	635	2.0	1372	30	CFRP	291	0.93	0.167	0.32	447	1.56	30.41	6330	1.00
$RO2_C$_S	457	457	1.0	1016	30	CFRP	291	0.93	0.167	0.58	446	1.48	32.25	7381	1.11
$RO3_C$_S	457	457	1.0	1016	30	CFRP	291	0.93	0.167	0.29	446	1.48	32.08	7088	1.06
$RO2_D$_S	648	648	1.0	1372	30	CFRP	291	0.93	0.167	0.52	446	1.48	30.88	15325	1.19
$RO3_D$_S	648	648	1.0	1372	30	CFRP	291	0.93	0.167	0.21	446	1.48	30.65	14035	1.07
$RO2_F$_S	324	324	1.0	1372	30	CFRP	291	0.93	0.167	0.41	447	1.53	31.52	3841	1.14
$RO2_G$_S	914	914	1.0	1981	30	CFRP	291	0.93	0.167	0.58	690	1.5	31.65	30857	1.14
$RO2_H$_R	635	1270	2.0	2743	30	CFRP	291	0.93	0.167	1.50	690	1.52	30.30	31146	1.19
DL2_S	610	610	1.0	3048	25	GFRP	76.9	4.70	0.246	0.81	414	1.10	48.62	17814	1.14
DL3_S	610	610	1.0	3048	25	GFRP	72.4	4.50	0.589	0.77	414	1.10	37.12	13002	1.05
DL4_S	610	610	1.0	3048	25	HFRP	82.9	3.93	0.120	0.63	414	1.10	44.40	15595	1.08
DL2a_R	508	737	1.45	3048	25	HFRP	82.9	3.93	0.120	0.64	414	1.09	47.59	17036	1.04
DL2b_R	356	508	1.43	3048	25	GFRP	76.9	4.70	0.246	1.18	414	1.13	51.09	8656	1.14
DL3b_R	356	508	1.43	3048	25	GFRP	72.4	4.50	0.589	1.13	414	1.13	46.40	7112	1.00
DL4b_R	356	508	1.43	3048	25	GFRP	72.4	4.50	0.589	2.82	414	1.13	49.72	8736	1.18
DL5b_R	356	508	1.43	3048	25	HFRP	82.9	3.93	0.120	0.92	414	1.13	46.79	7971	1.13