EFFECT OF SEISMIC RETROFITTING BY GRADED CARBON FIBER SHEET CONFIGURATION ON CIRCULAR STEEL BRDIGE PIER

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1. INTRODUCTION

Circular steel piers, which are commonly used in urban areas, are prone to locally buckle under a strong earthquake. Carbon fiber (CF) sheet wrapping is being promoted as a seismic retrofitting because CF sheets are lightweight, high-strength, and durable materials that are easy to install. CF sheet wrapping method has been supported by several studies to improve the load-carrying capacity and durability. However, it results in a diamond buckling which drastically decreases the load-carrying capacity upon failure. In this study, the ability of the graded configuration of CF sheet to improve the seismic performance of steel piers is examined by finite element analysis (FEA).

2. SPECIMEN DESIGN

2.1 Circular Steel Column

The target specimen in this study was a JIS STK400 grade steel (hollow circular cross-section) as shown in **Fig. 1**. The material properties are summarized in Table 1. Stiffening ribs and a section change were incorporated in the specimen to prevent buckling near the base of the column. The test specimen was subjected to a constant vertical load to represent the superstructure weight which was set as 10% (492.9 kN) of the yielding axial force. An increasing cyclic horizontal load is then applied at the top of the specimen by displacement control using the loading program as shown in **Fig. 2**. The calculated yield horizontal displacement (δ_y) of the column specimen is 10 mm. The dimensions of the specimen and the loading configuration were adopted from an existing experimental study (Okazaki et al. 2017).

2.2 CF Sheet Reinforcement

Two CF sheet configurations, shown in **Fig. 3**, were employed for the study: uniform design and graded design. The uniform design (R-U) uses a unidirectional CF sheet of equal layers in the circumferential direction throughout the range. An optimum nine layers of CF sheet, as confirmed by FEA, was used for the uniform design.

The graded design (R-G) aims to optimize the CF sheet reinforcement by increasing the range of reinforcement and by providing more reinforcement in the region where stress is concentrated. The number of layers for the graded configuration was set to have a volume approximately equal to that of the uniform configuration. The optimum number of layers for graded design was determined by FEA as well. The models used are summarized in **Table 2**.

The high-strength CF sheet and epoxy resin used in the previous experimental study were used for material properties. The resulting properties of the CF reinforced polymer (CFRP) is calculated using the Halpin-Tsai equations and are shown in **Table 1**.

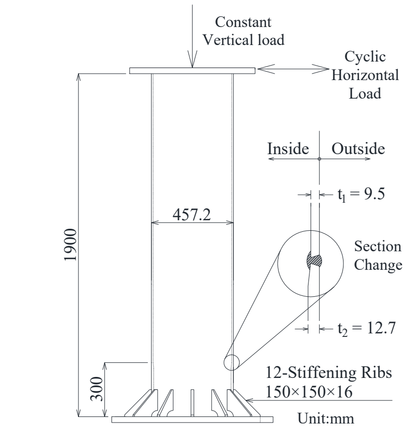


Fig. 1 Schematic view of test specimen

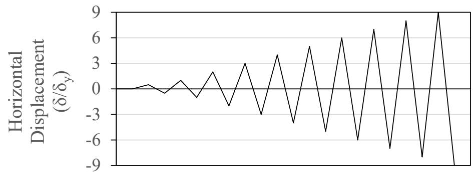
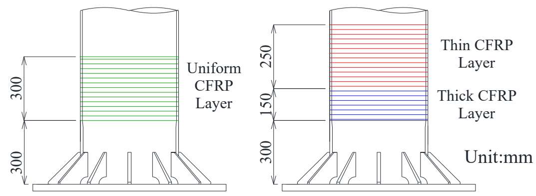


Fig. 2 Loading Program



(a) Uniform Design (b) Graded Design

Fig. 3 Reinforcement configuration

Table 1 Material properties

Materials	Properties	Symbols	Units	Values
Steel plate (STK400)	Yield Stress	σ_y	MPa	368.9
	Elastic modulus	E_s	MPa	205,000
CF sheet (UT70-30G)	Elastic modulus	E_{cf}	MPa	245,000
	Design thickness	t_{cf}	mm	0.167
	Poisson's ratio	ν_{cf}	-	0.2
Epoxy resin (AUR80)	Elastic modulus	E_m	MPa	2,500
	Thickness	ν_m	mm	0.28
CFRP	Fiber content	V_f	%	50
	Thickness	t_{cfrp}	mm	0.334
	Elastic modulus	E_l	MPa	111,400
	Elastic modulus	E_t	MPa	9,600
	Shear Modulus	G_{lt}	MPa	2,900
	Poisson's ratio	ν_{lt}	-	0.24

Table 2 Summary of models

Model	Classification	No of CF sheet	CFRP ratio
N	No reinforcement	-	-
R-U	Reinforcement	9	1
R-G1	Reinforcement	10 & 4	0.926
R-G2	Reinforcement	11 & 4	0.981

3. FINITE ELEMENT MODEL

3.1 Modeling of specimen

Finite element analysis was performed using the large strain nonlinear procedure of the general-purpose finite element program MSC Marc/Mentat 2019. The steel specimen and CFRP were modeled using 4-node thick shell elements as shown in **Fig. 4**. The region within reinforcement was modeled using a mesh of 10 mm x 20 mm to accurately model the buckling while the other regions were modeled using a larger 20 mm x 20 mm mesh.

Keywords: Carbon fiber sheet, Circular steel bridge pier, Finite element analysis
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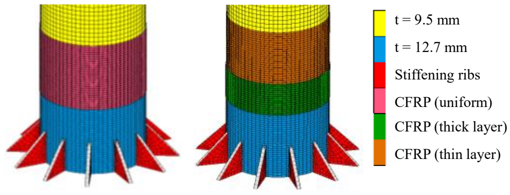
The steel was modeled as an isotropic elasto-plastic material with a kinematic hardening model of plasticity while the CFRP is modeled as elastic orthotropic material using the values in **Table 1**. Steel and CFRP elements were bonded together using the contact analysis option of MSC Marc/Mentat 2019. The glued cohesive contact was used and the contact stiffness (k_n=17150 N/mm^3, k_t=6170 N/mm^3) was obtained from the elastic modulus of the epoxy primer (AUP40).

3.2 Verification of Finite Element Model

The no-reinforcement (N) and reinforcement (R) specimens examined in the reference study (Okazaki et al. 2017) were created using the finite element model for verification. The comparison between the experimental and analytical peak envelope curves is shown in **Fig. 5**. A good agreement between the maximum horizontal load was observed with an average error of 2.90% and 2.93% for the N and R models, respectively. However, there is a difference in the slope of the envelope curves which can be attributed to the friction of the baseplates at the base of the specimen during the experiment which was not considered in the analytical model.



(a) Uniform Design (b) Graded Design

Fig. 4 Finite element model

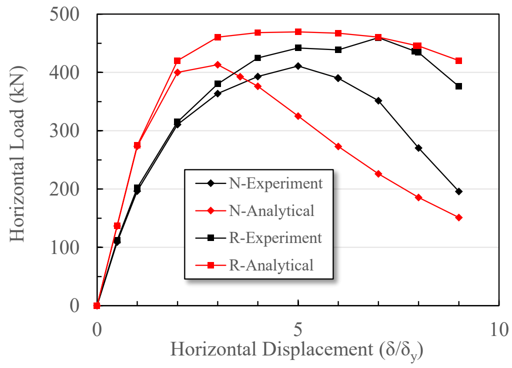


Fig. 5 Comparison experimental and analytical results

4. RESULTS AND DISCUSSION

4.1 Horizontal Load and Displacement Relationship

The relationship between load and displacement of the test specimens are shown in the peak envelope curves in **Fig. 6**. The maximum horizontal load-carrying capacity of the specimens is summarized in **Table 3**. It can be seen that all reinforcement models (R-U, R-G1 & R-G2) improved the load-carrying capacity. However, it can be observed that there was no significant difference between the horizontal load-carrying capacity of the uniform and graded design. R-G1 increased the capacity by just 1.45% whereas R-G2 improved the capacity by 2.34%. Although the difference is minimal, the maximum load for the both graded designs was reached at a higher interval of $\pm 7\delta_y$ while for the uniform design the maximum load was reached earlier at $\pm 5\delta_y$ loading.

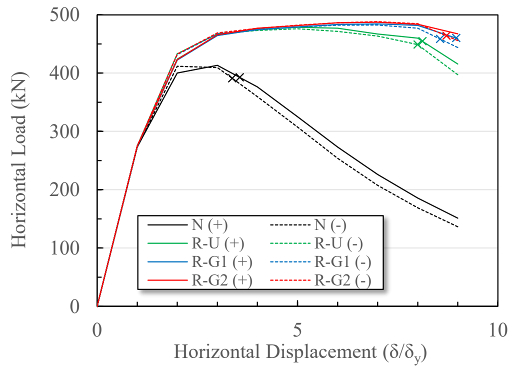


Fig. 6 Summary of envelope curves

Table 3 Comparison of maximum horizontal load

Model	(+) direction		(-) direction	
	H_{max} (kN)	% increase	H_{max} (kN)	% increase
N	413.21	-	-445.35	-
R-U	478.59	15.82%	-475.88	15.72%
R-G1	484.29	17.20%	-483.46	17.23%
R-G2	487.39	17.95%	487.87	18.30%

4.2 Ductility Evaluation

The ductility performance of the circular steel specimens was evaluated using the ductility parameter $\mu_{95} = \delta_{95}/\delta_y$, where δ_{95} corresponds to the displacement where failure occurred or maximum load dropped by 5%. The ductility parameters are summarized in **Table 4**. It was observed that the graded design delayed the failure or the column specimens by approximately 1 cycle in comparison to the uniform design. R-G1 improved the ductility performance by an average of 23.5% whereas R-G2 provides more than 26.5% compared to R-U specimen.

Table 4 Comparison of specimen ductility

Model	(+) direction		(-) direction	
	μ_{95}	% increase	μ_{95}	% increase
N	3.56	-	-3.37	-
R-U	8.12	128%	-7.78	131%
R-G1	8.96	152%	-8.56	154%
R-G2	9.00*	153%*	-8.72	159%

**Maximum load in R-G2 model only dropped by 4% at +9δy*

4.3 Buckling Deformation

Fig. 7 shows the buckling deformation at final loading of all the models. In the N model, elephant foot buckling (EFB) can be observed where the stress is concentrated on the bulge. The R-U has an inward bulge of approximately 32 mm at h=390 mm. The R-G1 model reduced the inward buckling to only 14 mm at the similar height. In the R-G2 model, however, buckling did not occur in the region of reinforcement but at h=280 mm and a smaller inward buckling of 11 mm which can be attributed to the additional layer of CF sheet in R-G2.

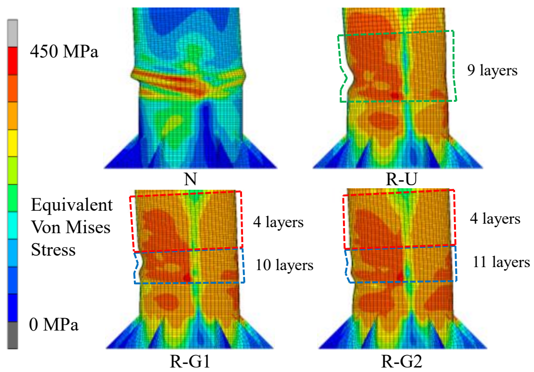


Fig. 7 Buckling deformation at final loading (-9δ$_y$)

5. CONCLUSION

The graded design configuration of CF sheets has no significant effect on the horizontal load-carrying capacity but can be effective in improving the ductility by delaying the progression of buckling. R-G1 and R-G2 model provided better performance compared to the uniform design model and will be further examined in an experimental study.

REFERENCES

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