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인발성형 FRP 복합소재 기둥부재의 크리프거동에 대한 실험적 분석

Experimental Investigation on the Creep Behavior of Pultruded FRP Composite Columns

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ABSTRACT

This paper presents the results of an experimental investigation pertaining to the creep behavior of fiber-reinforced polymeric (FRP) pultruded components subjected to sustained eccentric axial loading. Six different axial load/eccentricity combinations were investigated through the experiments. The test duration of these experiments was 2,000 hours (90 days), during which the mid-height lateral deflections of the components were recorded continually. Analytical formulations based on the Schapery's quasielastic method and a power law model were used for the prediction of the creep lateral deflection.

1. INTRODUCTION

The application of fiber-reinforced polymeric (FRP) composite structural shapes manufactured by the pultrusion process has grown very rapidly in the civil and structural engineering industry during the past 20 years. Despite many advantages, engineers are hesitant in using pultruded FRP composite components because of the limited information concerning the long-term creep behavior of such components under sustained loads.

Holmes and Rahman (1980) studied the creep behavior of hand-layered glass reinforced plastic box shape beams using four point bending tests for a period of 14,400 hours. Mottram (1993) studied the creep behavior of E-glass/polyester pultruded beam assembly made of two pultruded I beams bonded with pultruded plates at the top and the bottom under a three-point bending setup for 24 hours. Scott and Zureick (1998) investigated experimentally the creep behavior of pultruded E-glass/vinylester composite coupons in compression for a duration of 10,000 hours.

Findley (1944) proposed a mathematical equation for representing the creep behavior of plastics in the form of power function $\varepsilon(t)=\varepsilon_0+m\cdot t^n$. Vinogradov (1987) introduced approximate viscoelastic solutions for the creep and creep buckling behaviors of viscoelastic beam-columns under various loading conditions using a quasielasitc method that was originally proposed by Schapery (1965).

The objective of the present study is to investigate analytically and validate experimentally the creep behavior of pultruded FRP composite components under sustained eccentric axial loading.

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2. PREDICTION FORMULAE

Consider a square tube structural component and the cartesian coordinate system (x, y, z) as shown in Figure 1.

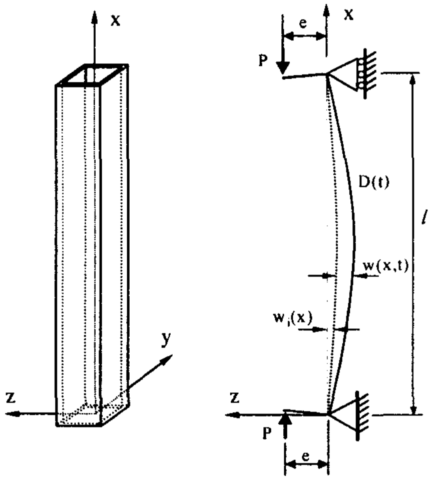


Figure 1: Component under Eccentric Axial Loading

The governing differential equation for the lateral deformation w(x, t) of the component can be written as follows:

$$\frac{D_{y0}}{[1+\psi_c(t)]}\frac{d^2}{dx^2}w(x,t) = -P \cdot \{e + w_i(x) + w\ (x,t)\} \tag{1}$$

In the above equation, D_{y0} is the short-term instant bending stiffness of the component about the y-axis, $\psi_c(t)$ is a creep function of the component, and $w_i(x)$ is the initial imperfection of the component assumed to have a sinusoidal shape of $w_i(x) = A_i sin(\pi x/l)$. The lateral deflection at the mid-height of the component, at x = $l/2$, is obtained as follows:

$$\delta(t) = e\{sec\frac{\pi}{2}\sqrt{\lambda[1+\psi_c(t)]} - 1\} + A_i\frac{\lambda[1+\psi_c(t)]}{1-\lambda[1+\psi_c(t)]} \tag{2}$$

where

$$\lambda = \frac{P}{P_{cr}} = \frac{P}{D_{y0}}\frac{l^2}{\pi^2} \quad \text{and} \quad k(t) = \frac{\pi}{l}\sqrt{\lambda\{1+\psi_c(t)\}} \tag{3}$$

For its simplicity and wide applicability, the Findley's power law of Equation 4 can also be used to examine the experimental creep behavior of pultruded FRP components subjected to sustained eccentric axial loading.

$$\delta(t) = \delta_0 + m_c t^{n_c} = \delta_0[1+\psi_c(t)] \tag{4}$$

In the above equations, $\psi_c(t)$ is the creep function expressed in the form:

$$\psi_c(t) = \frac{t^{n_c}}{\beta_c} \tag{5}$$

3. EXPERIMENTAL PROGRAM

Test components had the cross sectional dimension of 101.6 x 101.6 x 6.35 mm (b x b x t) and the material constitution of E-glass/polyester system with a fiber content of 35% by volume (23% of rovings and 12% of CSM's). Figure 2 shows the cross sectional configuration of the test components.

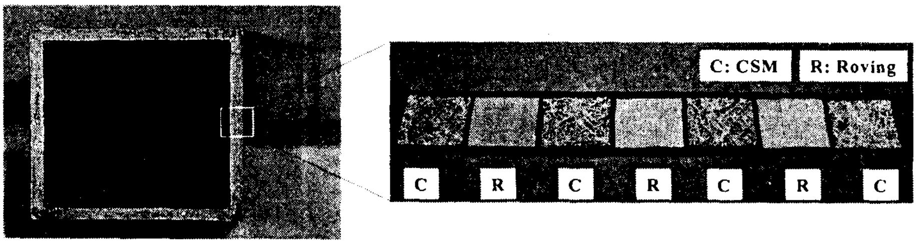
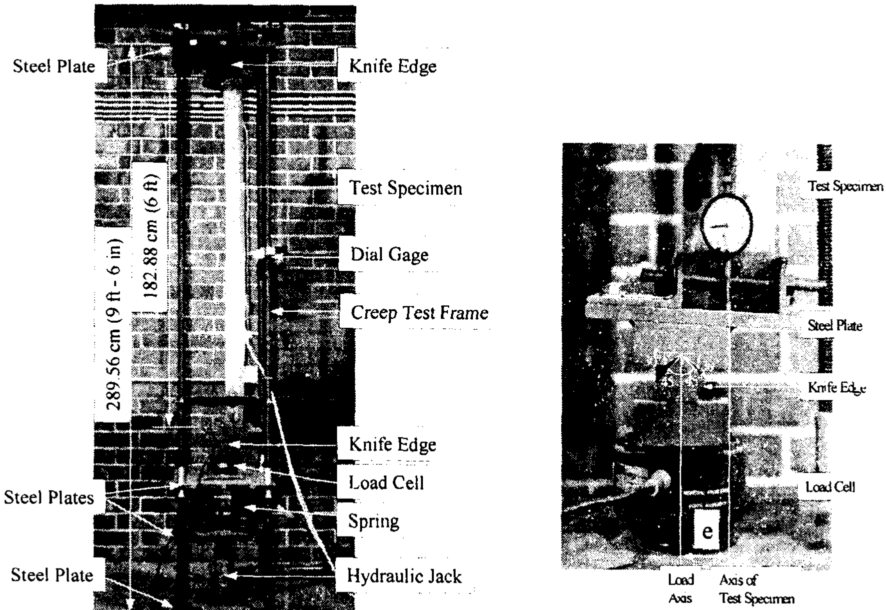


Figure 2: Component Cross Section and Layup

A test setup used for the experiments is shown in Figure 3 which shows a test specimen, test frames, knife edge supports, a load cell, springs, and a hydraulic jack. Knife edge supports were used at the top and bottom ends of the test specimen to permit one-sided in-plane rotation.



(a) Overall Setup (b) Single Knife Edge Setup

Figure 3: Creep Test Setup

The axial load on the specimen was applied by means of a hydraulic jack placed under the lower middle plate; i.e., the plate was forced to move up by using the hydraulic jack in order to generate the load. When the desired load was reached, the lower middle plate was fastened by the nuts at the top and at the bottom of the plate, and the hydraulic pressure in the jack was released.

A dial gage having 0.025 mm precision was placed at the middle of the specimen to measure the lateral deflection. Data were recorded after the following manner 1) immediately after axial loading was applied; 2) at the increasing time intervals of 30 minutes through 6 hours for the first day after the loading; 3) every day for the next 20 days; and 4) twice a week thereafter for the rest period of the experiment.

Table 1 shows the six different axial load/eccentricity combinations chosen for the creep tests of components subjected to sustained eccentric axial loading at both ends in the present study.

Table 1: Test Matrix of Load/Eccentricity Combinations (Refer to Figure 4)

e	e/b	P/P_{cr}		
		0.13	0.19	0.28
12.7 mm	0.125		○	
25.4 mm	0.25	○	○	○
50.8 mm	0.5	○	○	

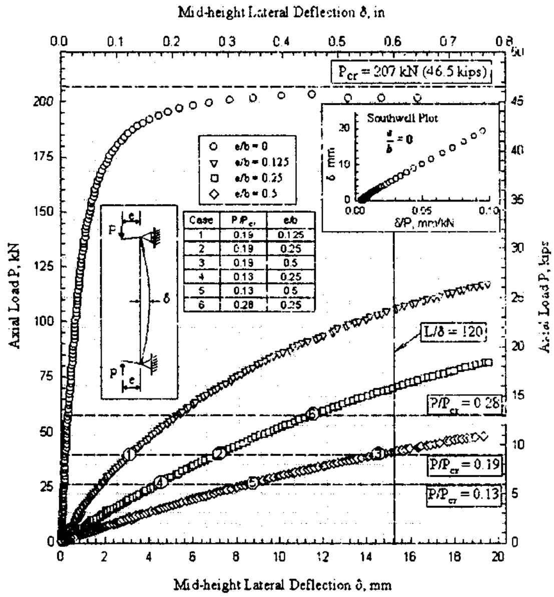


Figure 4: Instantaneous Mid-Height Lateral Deflections

4. EXPERIMENTAL RESULTS AND EVALUATION

The experimental results of the mid-height lateral deflection due to creep for P/P_{cr} are tabulated in Table 2 and Table 3 at selected time intervals of 0, 100, 500, 1,000, and 2,000 hours. The measurements of the instantaneous mid-height lateral deflection, δ_0, are also given in the tables.

Table 2: Creep Lateral Deflections at Mid–Height (Setup–I)

	P/P_{cr} = 0.19		P/P_{cr} = 0.19		P/P_{cr} = 0.19	
	e/b = 0.125		e/b = 0.25		e/b = 0.5	
δ_0	3.861 mm		7.417 mm		14.072 mm	
Time Hours	$\delta(t) - \delta_0$ mm	$(\delta(t) - \delta_0)/\delta_0$ %	$\delta(t) - \delta_0$ mm	$(\delta(t) - \delta_0)/\delta_0$ %	$\delta(t) - \delta_0$ mm	$(\delta(t) - \delta_0)/\delta_0$ %
0	0	0	0	0	0	0
100	0.198	5.1	0.318	4.3	0.592	4.2
500	0.254	6.6	0.497	6.7	0.968	6.9
1,000	0.279	7.2	0.565	7.6	1.138	8.1
2,000	0.351	9.1	0.630	8.5	1.278	9.1

Table 3: Creep Lateral Deflections at Mid–Height (Setup–II)

	P/P_{cr} = 0.13		P/P_{cr} = 0.13		P/P_{cr} = 0.28	
	e/b = 0.25		e/b = 0.5		e/b = 0.25	
δ_0	4.445 mm		8.763 mm		10.795 mm	
Time Hours	$\delta(t) - \delta_0$ mm	$(\delta(t) - \delta_0)/\delta_0$ %	$\delta(t) - \delta_0$ mm	$(\delta(t) - \delta_0)/\delta_0$ %	$\delta(t) - \delta_0$ mm	$(\delta(t) - \delta_0)/\delta_0$ %
0	0	0	0	0	0	0
100	0.201	4.5	0.440	5.0	0.607	5.6
500	0.289	6.5	0.596	6.8	0.885	8.2
1,000	0.319	7.2	0.700	8.0	0.962	8.9
2,000	0.338	7.6	0.682	7.8	0.994	9.2

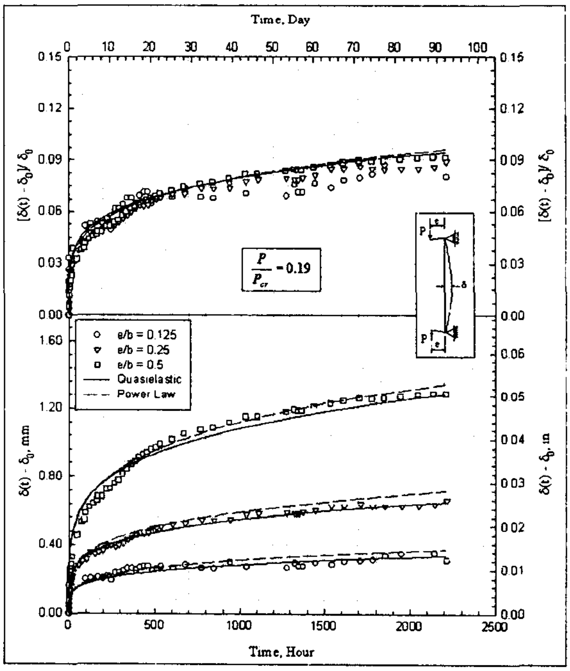


Figure 5: Creep Lateral Deflection at Mid–Height when P/P_{cr} = 0.19

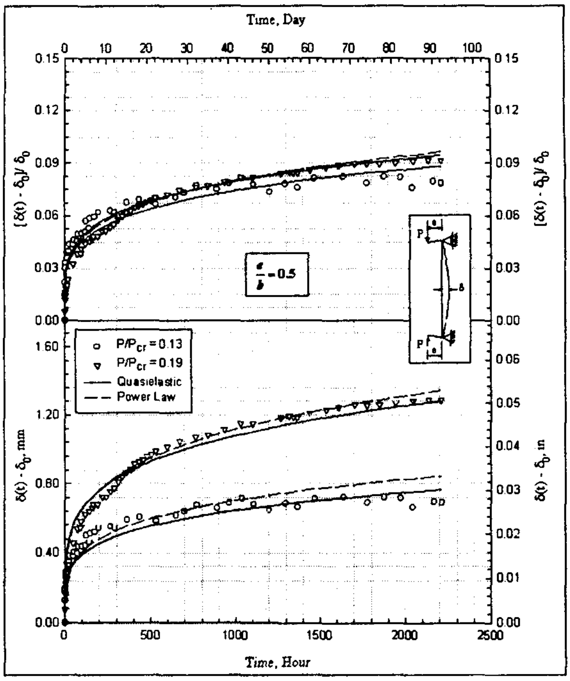


Figure 6: Creep Lateral Deflection at Mid-Height when e/b = 0.5

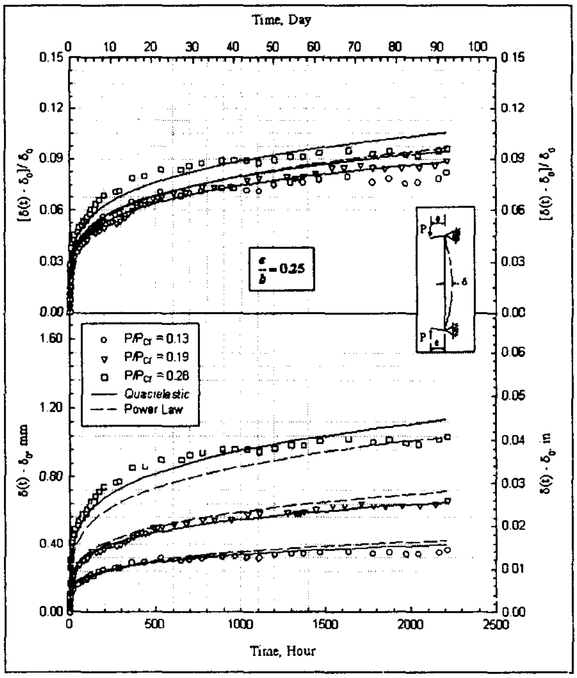


Figure 7: Creep Lateral Deflection at Mid-Height when e/b = 0.25

The parameters, β_c and n_c, of the creep functions, $\psi_c(t) = t^{n_c}/\beta_c$, in Equation 2 and Equation 4 were evaluated by the nonlinear regression analysis of the creep mid-height lateral deflection data. The results are summarized in Table 4. It should be noted that n_c is non-dimensional and β_c has the unit of $hour^{n_c}$.

Table 4: Creep Parameters

	P/P_{cr}	e/b	Quasielastic Formula Equation 4		Power Law Model Equation 5	
			β_c	n_c	β_c	n_c
CR1	0.19	0.125	69	0.207	65	0.214
CR2	0.19	0.25	75	0.239	72	0.254
CR3	0.19	0.5	70	0.237	67	0.255
CR4	0.13	0.25	66	0.208	63	0.237
CR5	0.13	0.5	65	0.195	55	0.203
CR6	0.28	0.25	62	0.200	56	0.241
Average			67.8	0.214	63.0	0.234
STD			4.5	0.019	6.5	0.021
COV(%)			6.7	8.8	10.4	9.1

The experimental results are presented in Figure 5 thru Figure 7 with the values obtained analytically using the quasielastic equation (Equation 2) and the power law equation (Equation 4). It is of interest to note that the values of β_c and n_c are in the range of those experimentally obtained by Scott and Zureick (1998) for a pultruded material using compression coupon creep tests. In their experiments, β = 65.6 (48.1 ~ 81.4) and n = 0.228 (0.207 ~ 0.243) were evaluated from strain data by applying the following equation.

$$\epsilon(t) = \epsilon_0 + mt^n = \epsilon_0[1 + \psi(t)] = \epsilon_0[1 + \frac{1}{\beta}t^n] \quad (6)$$

Cautions must be exercised when Equation 2 and Equation 4 are used to predict the long-term deflection of the component subjected to sustained eccentric axial loading over a time duration greater than that of the experiment. The predictive equations are subjected to the following assumptions:

1) Small deformation theory holds and creep buckling does not occur. Thus, if one considers the equation of $\lambda = P/P_{cr} < 1/\{1+\psi_c(t)\}$ where $\psi_c(t) = (8760t^{0.25})/50$, a maximum value of λ = 0.6 should be in effect.

2) Creep rupture does not occur during the service life of the component. Sridharan (1997) estimated that the creep rupture life of a similar pultruded composite material subjected to 30% ultimate stress was 190 years and 15 years when exposed to dry air and water, respectively, at 25C.

3) The assumption of linear viscoelastic behavior of the material applies. Scott and Zureick (1998) recommended that the average stress for a similar composite material not exceed 60% of the ultimate compressive strength of the material.

5. CONCLUSION

Based on the results of the experimental and analytical investigations in the present work, the following conclusions are made:

1) Quasielastic equations formulated for estimating the time-dependent lateral deflection of FRP components subjected to sustained eccentric axial loading are governed by the ratio of the sustained load over the buckling load $\lambda = P/P_{cr}$, the load eccentricity e, and the creep function of the component $\psi_c(t)$.

2) For the pultruded material under eccentric axial loading, 75% of the total creep for the test period of 2,000 hours occurred during the first 500 hours.

3) The time-dependent bending stiffness of FRP components subjected to sustained eccentric axial loading, $D_c(t)$, can be estimated from the following equation:

$$D_c(t) = \frac{D_{c0}}{1+\psi_c(t)} = \frac{D_{c0}}{1+\dfrac{1}{\beta_c(8760t)^{n_c}}} \tag{7}$$

where D_{c0} is the short-term instant bending stiffness of the component, and t is the time in years. For an E-glass/polyester system with a fiber content of approximately 35% by volume (23% of rovings and 12% of CSM's), the recommended values of the parameters β_c and n_c are 60 and 0.25, respectively.

BIBLIOGRAPHY

1. Findley, W.N. (1944), "Creep Characteristics of Plastics," Symposium on Plastics, American Society for Testing Materials, pp. 118-134.
2. Holmes, M. and Rahman T.A. (1980), "Creep Behavior of Glass Reinforced Plastic Beams," Composite, Vol. 11, No. 2, pp. 79-85.
3. Mottram, J.T. (1993), "Short- and Long-term Structural Properties of Pultruded Beam Assemblies Fabricated Using Adhesive Bonding," Composite Structures, Vol. 25, pp. 387-395
4. Schapery, R.A. (1965), "A Method of Viscoelastic Stress Analysis Using Elastic Solutions," Journal of Franklin Institute, Vol. 279, 1965, pp. 268-289.
5. Scott, D.W. and Zureick, A. (1998), "Compression Creep of A Pultruded E-glass/Vinylester Composite," Composites Science and Technology, Vol. 58, pp. 1361-1369.
6. Sridharan, S. (1997), "Environmental Durability of E-glass/Vinylester Composites in Hot-Moist Conditions," Ph.D. Dissertation, Georgia Institute of Technology.
7. Vinogradov, A.M. (1987), "Buckling of Viscoelastic Beam Columns," AIAA Journal, Vol. 25, No. 3, pp. 479-483