Modeling of Parachute Opening: An Experimental Investigation

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Scaling parameters for the peak opening force and opening time of solid cloth parachutes are investigated using the physical modeling technique. With Froude number and mass ratio as the two scaling parameters, correlation of the nondimensional peak opening force and opening time between the full-scale and the model parachutes made from the same 1.1 oz/yd² ripstop nylon was not entirely satisfactory. Nylon fabrics with areal densities up to 14 oz/yd² were then used to construct full-scale parachutes so that the 1.1 oz/yd² model parachute would have a lighter fabric. This improved the correlation between the full-scale parachutes and the model parachute and established the importance of scaling canopy fabric as well as Froude number and mass ratio for modeling parachute opening.

Nomenclature

D_{max} = maximum measured width of canopy when a parachute is hung upside down by its risers
D_0 = constructed canopy diameter
F_o = parachute opening force
F_p = peak opening force
F_s = snatch force
Fr = Froude number
g = gravitational acceleration
K_p = parachute spring constant
k_s = spring constant of a suspension line
M_r = mass ratio based on the total mass of payload and parachute
$M_{r,l}$ = mass ratio based on payload mass
$M_{r,p}$ = mass ratio based on parachute mass
m_l = payload mass
m_p = parachute mass
S_o = surface area of a constructed canopy
t_o = parachute opening time
t_p = time instant when peak opening force occurs
t_s = time instant when canopy snatch occurs
v_s = snatch velocity
W_c = constructed canopy weight
w_{cl} = areal density of canopy fabric
X_p = nondimensional peak opening force based on the total mass of payload and parachute
$X_{p,l}$ = nondimensional peak opening force based on payload mass
η = canopy stiffness index
ρ_a = air density
τ = nondimensional opening time

Introduction

SIMULATION techniques for airdrop systems have not been well developed and need to be investigated. This deficiency is primarily due to the difficulty in modeling the performance of parachutes, which are an important part of an airdrop system. Parachutes are difficult to model because they are flexible, porous structures that change shape and interact with the surrounding air during an airdrop operation.

A typical aerial delivery operation using parachutes is shown in Fig. 1. In Fig. 1a, the extraction parachute has pulled the payload and the main recovery parachute from the airplane. In Fig. 1b, the extraction parachute deploys the main recovery parachute from the deployment bag. The suspension lines of the main recovery parachute are fully extended, and the deployment bag and the extraction parachute are being released. Subsequently, the parachute interacts with the surrounding flowfield, changes its shape, captures air mass, and finally inflates to its fully opened shape as shown in Figs. 1c and 1d. During this inflation process, an opening force is generated by the parachute as it decelerates the payload. A typical time history of the opening force is shown in Fig. 1e. Two important parameters in the process are the peak opening force F_p and opening time t_o, which is the time interval between the time t_s when snatch force F_s occurs and time t_p when F_p occurs. Peak opening force is important because it governs canopy structural requirements, and opening time is an important parameter in opening dynamics and trajectory.

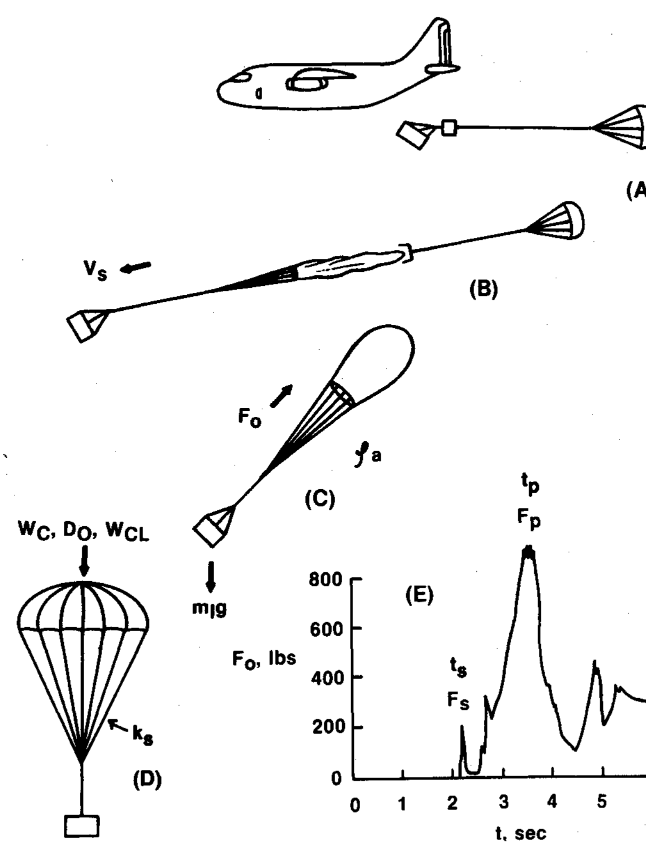

Fig. 1 Schematic of an airdrop operation (A–D) and typical time history of parachute opening force (E).

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In view of the importance of F_p and t_o, they were investigated by Berndt and DeWeese[1,2] for 28-ft-diam, full-scale, solid cloth, C9 personnel parachutes at various altitudes and payload weights, and by Heinrich and Noreen[3] and Heinrich and Hektner[4] for 3- and 5-ft diam, solid cloth, model parachutes. They pointed out the importance of the flexibility of model parachute canopies on their opening characteristics relative to those of full-scale parachutes. The flexible structure of the canopy is a factor that inhibits the advancement of parachute modeling. (However, it is also the factor that gives a parachute its advantages and characteristics of high drag per unit weight and packed volume.) Heinrich and Hektner[4] introduced a parachute canopy stiffness index η in an effort to relate the opening characteristics of full-scale and model parachutes made of the same canopy fabric. They found that as the size of the parachute decreased, the canopy became stiffer, and the increasing stiffness was reflected in the increasing values of η.

French[5] attempted to correlate the peak opening forces and the opening times of full-scale parachutes of various kinds and sizes. Fu,[6] Lingard,[7] and Ludke[8] derived scaling parameters for parachute performance; no experimental evidence was obtained on full-scale and model parachutes to substantiate their findings. Barton[9] and Saliaris[10] also derived parachute scaling relationships and did large-scale parachute tests, but the problems of small-scale model parachutes and canopy stiffness were not addressed. Moore et al.[11] and Eichblatt et al.[12] conducted analysis and experiments on modeling of parawing opening.

More recently, Lee[13] did a systematic experimental investigation on the opening of full-scale C9 parachutes and ½- and ¼- scale C9 model parachutes made from 1.1 oz/yd² ripstop nylon, the same canopy fabric used for the full scale. A preliminary correlation of F_p and t_o between the full scale and the models was obtained. However, experimental data were not sufficiently extensive to substantiate the scaling relationships. The investigation continued, and additional results are presented in this paper.

Parachute Modeling Parameters

Based on the vertical equations of motion of a parachute-payload system and the work of Heinrich and Hektner[4] and Fu,[6] the four important independent scaling parameters for the nondimensional peak opening $X_{p,1}$ and the nondimensional opening time τ are Fr, the mass ratio $M_{r,1}$, the canopy stiffness index η, and the parachute spring constant K_p.[13] Expressions for these parameters are as follows:

$$Fr = v_s^2/gD_0 \qquad M_{r,1} = m_1/\rho_a D_0^3$$

$$\eta = \frac{D_{\max}}{D_0}\frac{W_c}{S_o w_{cl}} \qquad K_p = k_s D_0/m_l g$$

$$X_{p,l} = F_p/m_1 g \qquad \tau = v_s t_o/D_0$$

In deriving these parameters, the parachute mass m_p has been assumed to be negligible. For parachutes made from 1.1 oz/yd² nylon, this assumption is usually valid. However, if heavier nylons having areal densities higher than 1.1 oz/yd² are used, m_p may not be negligible when compared to m_1. In that case, X_p and M_r have the following expressions:

$$X_p = F_p\ (m_1 + m_p)g$$

$$M_r = m_1/\rho_a D_0^3 + m_p/\rho_a D_0^3 = M_{r,1} + M_{r,p}$$

Hence, in addition to scaling m_1, m_p also has to be scaled to satisfy the scaling of M_r of the parachute-payload system. In Lee's previous work for $M_{r,l} = 0.2$,[13] because of the light 1.1 oz/yd² nylon, the differences between X_p and $X_{p,l}$, and M_r and $M_{r,l}$ are less than 6%.

The aforementioned parameters obtained from outdoor opening tests, such as the vertical drop tests from a crane conducted by Lee,[13] generally show considerable scatter. This is shown in Fig. 2. Figure 2a shows opening force measurements of a ¼-scale model C9 dropped from a free-hanging position (without packing) for five tests conducted in a quiescent indoor environment. The data are very consistent, and the variation in F_p from the average is about 10%. When the same parachute was packed and dropped in a nonquiescent outdoor environment, the opening was much less consistent. This is shown in Fig. 2b, where opening force measurements from four identical outdoor drop tests are compared. It is noted that the variation in F_p from the average is about 30%, much higher than that of the indoor tests. The much higher variation is attributed to parachute packing, random canopy air flow interaction, and variable outdoor wind conditions.

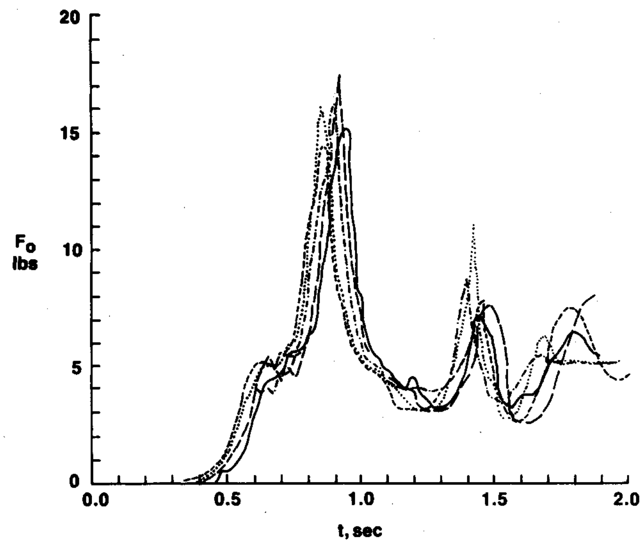


Fig. 2a Opening force from five indoor tests of a ¼-scale model C9 from a free hanging position.

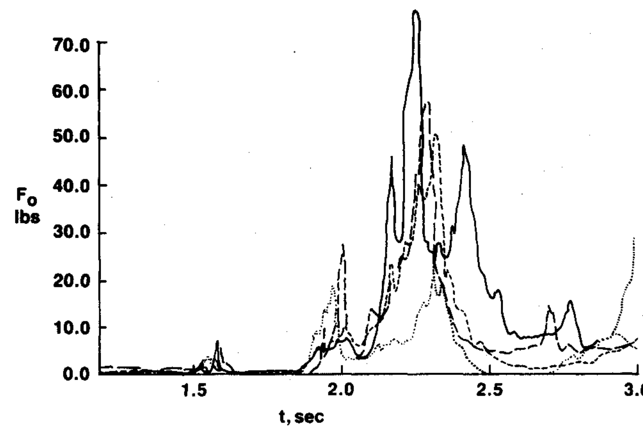


Fig. 2b Opening force from four outdoor tests of a packed ¼-scale model C9.

Current Modeling Work

Construction of Full-Scale Parachutes

Lee[13] previously found that X_p and τ of the 1.1 oz/yd², ¼-scale C9 model parachutes were higher and lower, respectively, than those of the full-scale C9 parachute for $M_r = 0.2$; η of the ¼-scale model was higher than that of the full scale, a similar result found by Heinrich and Hektner.[4] To investigate further, additional data were obtained for $M_r = 0.13$. Again, the same differences as for $M_r = 0.2$ were observed, as shown in Fig. 3. It is noted that the data scatter is consistent with that in Fig. 2b.

It became evident that using the 1.1 oz/yd² ripstop nylon of the full-scale C9 for the canopy of the ¼-scale model does not give good correlation in X_p and τ. The next logical step would be to construct and investigate less stiff models made from

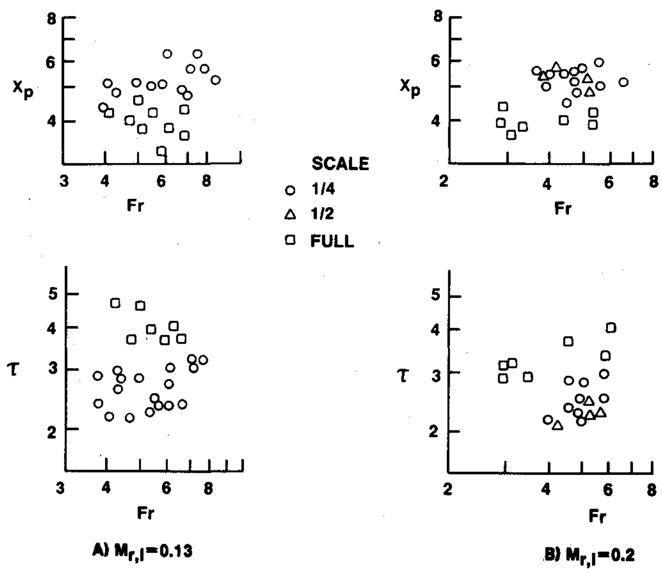


Fig. 3 Correlation of X_p and τ vs Fr between full-scale and small-scale model C9 parachutes made of 1.1 oz/yd^2 nylon.

Table 1 Physical properties of the nylon used for the canopies of the full-scale parachutes

		Heavy nylon C9		
	Standard C9	No. 1	No. 2	No. 3
Areal density, oz/yd^2	0.94 (1.1)[a]	4.1 (4.75)[a]	9.2 (10.0)[a]	12.2 (14.0)[a]
Thickness, in.	0.0028	0.0011	0.021	0.027
Air permeability, at 0.5 in. H_2O, ft^3/(min-ft^2)	72.5	53	22	31

[a]Military standard values.

lighter nylon fabrics. However, the lightest commercially available nylon was only 0.89 oz/yd^2, not much lighter than the 1.1 oz/yd^2 ripstop nylon. Faced with this constraint, it was decided to construct new full-scale C9 parachutes with heavier nylon fabrics so that the 1.1 oz/yd^2 nylon used for the model would be a lighter fabric relative to that used for the new full-scale parachutes. This idea was feasible because various heavy nylons are commercially available. In particular, three heavy standard military parachute nylon fabrics with areal densities of 4.75, 10, and 14 oz/yd^2 were chosen so that the effect of canopy stiffness could be examined progressively.

The three chosen heavy nylon fabrics were tested for their physical properties. They are tabulated in Table 1 along with those of the 1.1 oz/yd^2 ripstop nylon for comparison. It is noted that the actual areal densities of the nylon fabrics are lower than their standard military specifications. (The standard military values will be used throughout the text, and the actual values will be used in the figures.) Comparing to the 1.1 oz/dy^2 nylon, the areal densities of the heavy nylon fabrics are 4 to 12 times higher, and their permeability values are moderately lower. It was expected that both the higher areal density and the lower porosity would result in higher opening force and shorter opening time.

A better approach would be to vary areal density and porosity separately so that their effects could be investigated independently. However, this approach would require a long and expensive program in developing new nylon fabrics. For the current investigation, three new full-scale C9 parachutes were constructed using the three heavy nylons shown in Table 1. Except for the difference in canopy fabric, all the other components and the construction techniques of the three new parachutes were the same as those of the standard C9.

In addition to using heavier and less permeable nylon to obtain stiffer canopies, a standard 1.1 oz/yd^2 C9 parachute was modified in an attempt to increase its canopy stiffness. The modification included sewing a 1-$\frac{1}{16}$ in. wide × 0.045 in. thick piece of 1.15 oz/yd^2 nylon webbing on all 28 radial seams in the canopy of the standard C9. It was anticipated that such a reinforced or "ribbed" canopy would have increased its stiffness.

In an additional study on the effect of heavy nylon, the 4.75 oz/yd^2 nylon was also used to construct a ¼-scale model C9 so that its performance could be compared with that of the ¼-scale model C9 made from the 1.1 oz/yd^2 ripstop nylon in Lee's previous study.[13]

Stiffness Indexes of Full-Scale and Model Parachutes

Heinrich and Hektner's[4] parachute canopy stiffness index η was based on the opening characteristics of full-scale and small-scale parachutes made from the same 1.1 oz/yd^2 ripstop nylon. They showed that η was proportional to the stiffness of the parachute; as η increased, opening force increased and opening time decreased. They also showed that solid cloth model parachutes had higher η values than those of the standard solid cloth full-scale C9 parachutes.

Before the full-scale and model C9 parachutes were tested, their η values were investigated. The constructed canopy weight W_c of each canopy was measured first. The canopies were then hung upside down, as shown in Fig. 4, for D_{max} measurements to determine η.

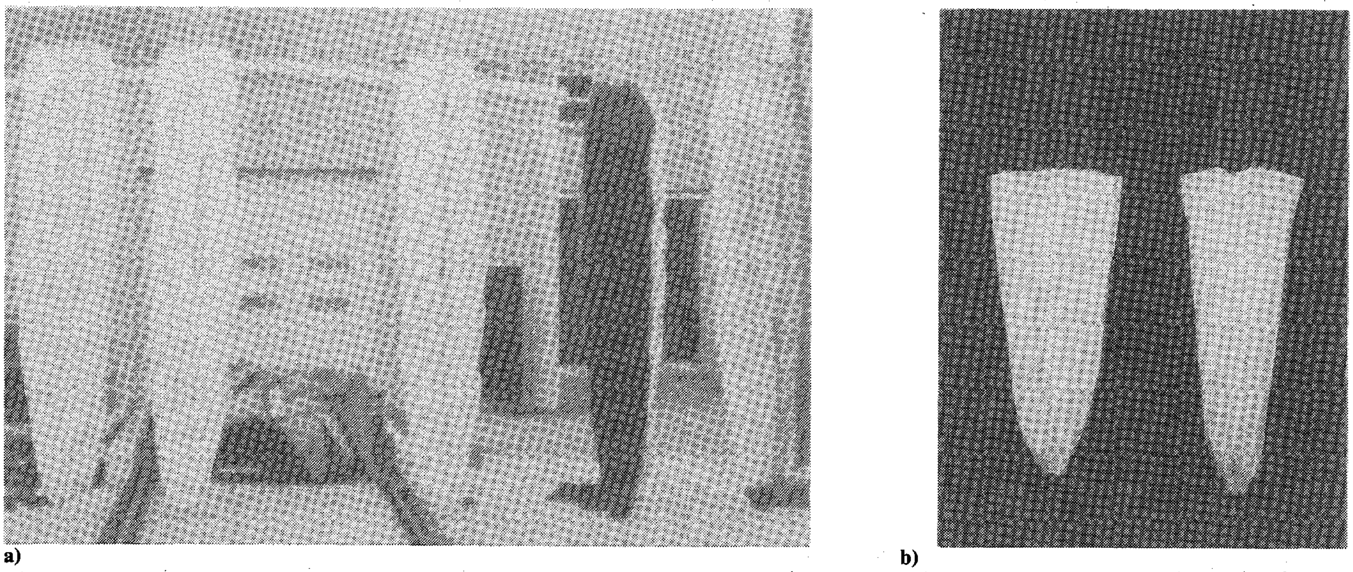
Measurements of W_c and D_{max} are shown in Table 2. As expected, W_c and constructed canopy areal density W_c/S_o increase considerably from the standard full-scale C9 to the heavy nylon full-scale C9's. In the standard full-scale C9 canopy, the webbings, suspension lines along the radials, and construction details (e.g., French seams of the radials) raise W_c/S_o to 3.27 oz/yd^2, more than three times the 1.1 oz/yd^2 nylon w_{cl}. However, in the heavy nylon, full-scale C9 canopies, the nylon fabric is the heavy component as compared to the other components. Consequently, W_c/S_o of the heavy nylon, full-scale C9's do not increase from their w_{cl} values as much as the standard full-scale C9 as shown in Table 2, part A. The result is that the ratio $W_c/(S_o w_{cl})$ decreases progressively from the standard C9 to the heavy nylon C9's as the nylon areal density increases. Similar reasoning and behavior also apply to W_c/S_o and $W_c/(S_o w_{cl})$ for the 1.1 and 4.75 oz/yd^2 ¼-scale model C9's, as shown in Table 2, part B.

As seen in Fig. 4a and tabulated in Table 2, part A, in spite of the heavy nylon, D_{max} and D_{max}/D_o of the heavy nylon full-scale C9's increase only slightly from those of the standard C9. As the canopy becomes smaller in the ¼-scale models, the increases in D_{max} and D_{max}/D_o are more pronounced as shown in Fig. 4b and Table 2, part B.

The net result of the behavior of $W_c/(S_o w_{cl})$ and D_{max}/D_o as discussed previously is that the product of the two variables that define η actually decreases from the standard full-scale C9 to the heavy nylon full-scale C9's, and remains about the same for the two ¼-scale model C9's. This behavior in η is opposite to what one might expect from the heavier and stiffer heavy nylon, full-scale and ¼-scale C9's.

On the other hand, when the η values of the parachutes made from the same 1.1 or 4.75 oz/yd^2 nylon are compared, i.e., parachute 1 compared to parachute 2 in Table 2, parachute 1 to parachute 6, and parachute 3 to parachute 7, η increases. This behavior in η is similar to that observed in the work of Heinrich and Hektner.[4]

Based on the aforementioned results, it appears that η behaves the way Heinrich and Hektner suggested only for parachutes made of fabric with the same areal density (which was how η was originally proposed). Extending η to parachutes made of fabrics with different areal densities may not be valid. For fabrics with different areal densities, perhaps Young's modulus and the moment of inertia should be considered for scaling the canopy stiffness.



a) b)

Fig. 4 Photographs showing C9 parachutes hung upside down for D_{max} measurements: a) full-scale (left to right): 14 oz/yd², 10 oz/yd², 4.75 oz/yd², reinforced 1.1 oz/yd², and standard 1.1 oz/yd²; b) ¼-scale (left to right): 4.75 oz/yd² and 1.1 oz/yd².

Table 2 Stiffness indexes of full-scale and model parachutes

Parchute	w_{cl}, oz/yd²	W_c, lb	W_c/S_o, oz/yd²	$W_c/(S_o w_{cl})$	D_{max}, in.	D_{max}/D_o	η
A. Full scale							
1. Standard C9							
2. Standard C9							
with added	0.94(1.1)[a]	9	2.19	1.99	26.0	0.0774	0.154
radials	0.94(1.1)[a]	14	3.27	2.97	26.5	0.0789	0.234
3. Heavy C9							
no. 1	4.1(4.75)[a]	29	6.78	1.65	27.5	0.0818	0.135
4. Heavy C9							
no. 2	9.2(10.0)[a]	56	13.1	1.42	28	0.0833	0.188
5. Heavy C9							
no. 3	12.2(14.0)[a]	73	17	1.39	28	0.0833	0.116
B. Models							
6. ¼-scale C9	0.94(1.1)[a]	0.373	1.39	1.26	13	0.155	0.195
7. ¼-scale C9	4.1(4.75)[a]	1.22	4.56	1.11	15	0.179	0.198

[a]Military standard values.

Importance of Parachute Mass

As shown in Table 2, W_c increases substantially for the parachutes made from heavy nylons. Table 3 shows the relative importance of W_c in terms of mass scaling of the payload and the canopy. In Table 3, W_c is represented by m_p, which is approximately equal to W_c because of the negligible weight of the suspension lines.

It is seen that $M_{r,p}$ becomes more significant when compared to $M_{r,1}$ as w_{cl} increases. Consequently, M_r becomes larger than $M_{r,1}$ for the heavy nylon parachutes. In the current work, $M_{r,1}$ is matched between the full scale and the ¼ scale; M_r is moderately different between the two. If there were a very low areal density nylon that could be used for the ¼-scale model, the difference between $M_{r,1}$ and M_r would be negligible.

Vertical Opening Experiments

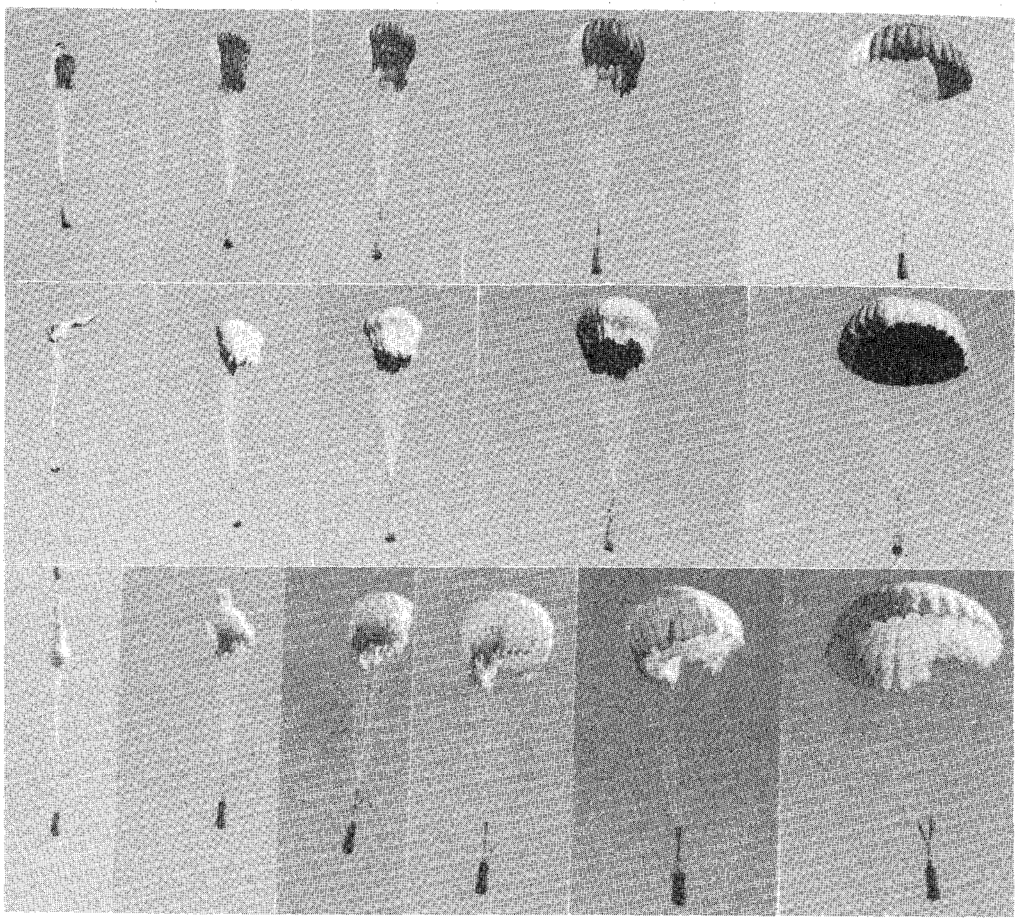
The same test setup and procedure used and described by Lee[13] were used for the current investigation. Briefly, a 280-ft crane was used to conduct vertical opening drop tests of the parachutes. Opening force and acceleration were measured during the tests. Acceleration measurements were then integrated to obtain velocity data. Finally, nondimensional parameters were calculated for correlation.

The main additions to the test facility were a remote control model airplane and a high-speed (3 frames/s) still-photograph camera. The remote-control airplane was found to be very useful and convenient for model parachute testing. Sequential still photographs taken of the parachutes during opening, as shown in Figs. 5 and 6, were helpful in visualization of and qualitative comparison between the opening of different parachutes.

Table 3 Mass comparison between payloads and parachutes

w_{cl}, oz/yd²	m_1, lb	m_p, lb	$M_{r,1}$	$M_{r,p}$	M_r
A. Full scale					
1.1[a]	336	9	0.2	0.0055	0.206
	220		0.13		0.136
4.75	336	29	0.2	0.018	0.218
	220		0.13		0.148
10.0	336	56	0.2	0.034	0.234
	220		0.13		0.164
14.0	336	73	0.2	0.044	0.244
	220		0.13		0.174
B. ¼ scale					
1.1	5.3	0.373	0.2	0.014	0.214
	3.5		0.13		0.144
4.75	5.3	1.22	0.2	0.047	0.247
	3.5		0.13		0.177

[a]Standard C9 parachute.

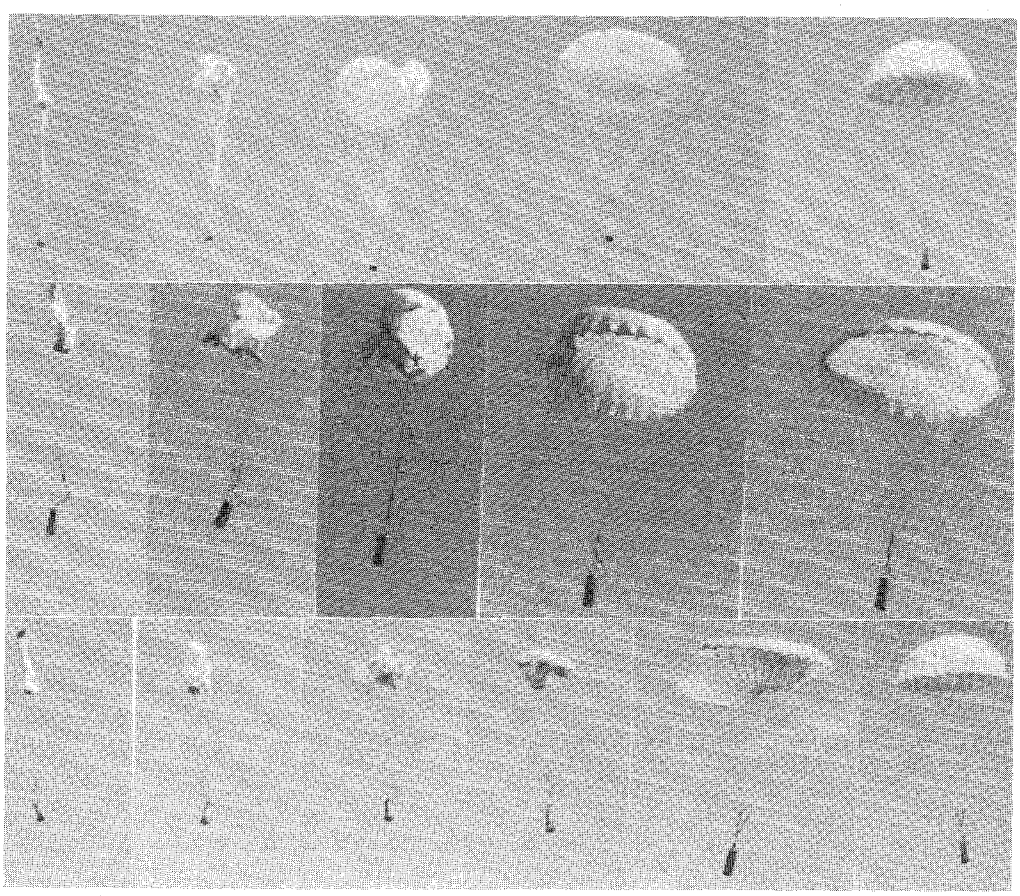


a)

b)

c)

Fig. 5 Photographs showing the opening of full-scale C9 parachutes: a) standard; b) reinforced; c) 4.75 oz/yd².



a)

b)

c)

Fig. 6 Photographs showing the opening of full-scale C9 parachutes: a) 10 oz/yd²; b) and c) 14 oz/yd².

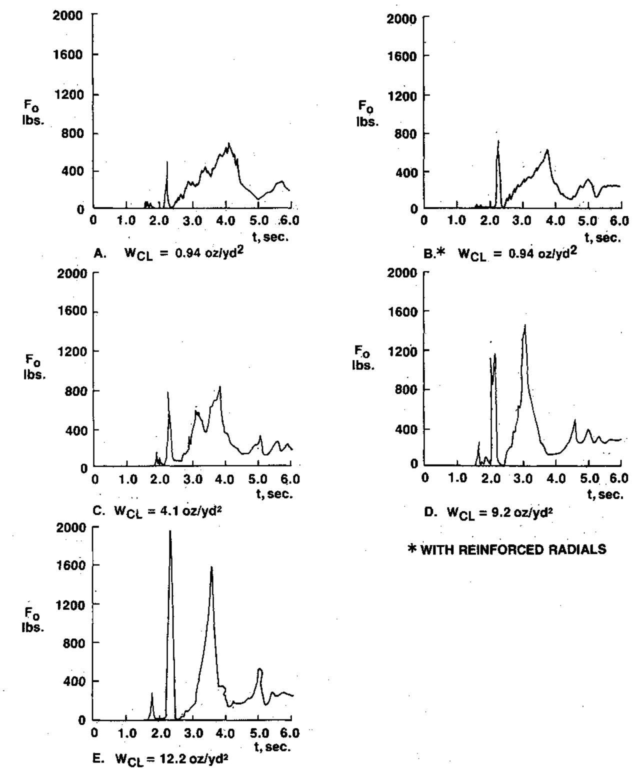


Fig. 7 Typical opening force measurements of full-scale C9 parachutes.

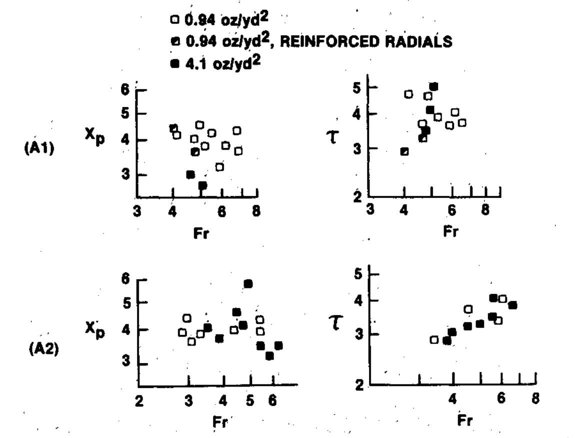


Fig. 8a Comparison of X_p and τ vs Fr between 1.1 and 4.75 oz/yd² full-scale C9 parachutes: A1) $M_{r,1} = 0.13$; A2) $M_{r,1} = 0.2$.

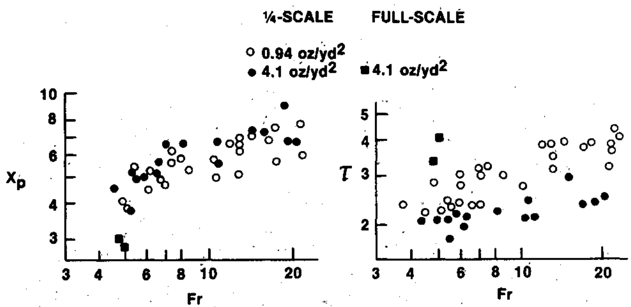


Fig. 8b Comparison of X_p and τ vs Fr for $M_{r,1} = 0.13$ between 1.1 and 4.75 oz/yd² ¼-scale model C9 parachutes and 4.75 oz/yd² full-scale C9 parachute.

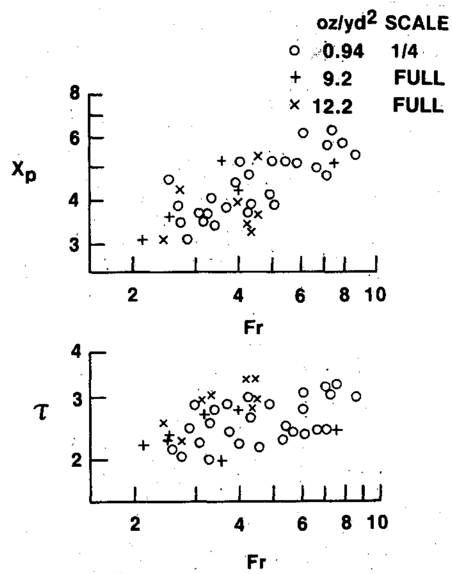


Fig. 9 Correlation of X_p and τ vs Fr for $M_{r,1} = 0.13$ between heavy nylon (10 and 14 oz/yd²) full-scale C9 parachutes and light nylon (1.1 oz/yd²) ¼-scale model C9 parachute.

Opening Force and Opening Time

Typical opening force measurements of the five full-scale C9 parachutes are shown in Fig. 7. The peak opening forces of the two 10 and 14 oz/yd² heavy nylon C9's are much higher than those of the other three 1.1 and 4.75 oz/yd² C9's; correspondingly, their opening times are also shorter. However, the opening forces and opening times of the 4.75 oz/yd² C9 and the two 1.1 oz/yd² C9's are not significantly different. These measurements show that increasing the nylon areal density from 1.1 to 4.75 oz/yd² and reinforcing the radials of the canopy does not significantly change the opening characteristics of the full-scale C9, but increasing the nylon areal density to 10 and 14 oz/yd² does significantly decrease opening time and increase opening force.

Close examination of Figs. 5 and 6 reveals that the opening of the two 10 and 14 oz/yd² heavy nylon full-scale C9's is quite different from that of the standard 1.1 oz/yd² full-scale C9. It is well known that a standard 1.1 oz/yd² C9 opens in two stages. The first stage consists of air filling the canopy from the skirt to the apex to form a cylindrical shape; the second stage consists of opening the canopy by air filling from the apex toward the skirt. These two stages are clearly shown in Fig. 5a. However, for the two heavy nylon C9's, the opening is more direct and less orderly, as shown in Fig. 6. The opening basically consists of filling the entire canopy all at once without going through two stages, as does the standard 1.1 oz/yd² C9. Apparently, the high air pressure in the apex during opening is not able to elongate the canopy because of the heavier and stiffer nylon; the result is that the canopy becomes a hemispherical shape faster than the 1.1 oz/yd² nylon canopy. Consequently, the opening time is shorter for the two heavy nylon C9's than for the 1.1 oz/yd² C9, as shown in Fig. 7.

The opening of the reinforced 1.1 oz/yd² C9 is not much different from that of the standard 1.1 oz/yd² C9, as shown in Fig. 5. However, some irregularity and somewhat less distinctive two-stage opening begins to show in the 4.75 oz/yd² C9, as shown in Fig. 5c.

Correlation of X_p and τ

From the measured opening force and acceleration as mentioned earlier, X_p, τ, and Fr were calculated for correlation between the full-scale and the model C9's.

Figure 8a shows the opening characteristics of the 1.1 and 4.75 oz/yd² full-scale C9's. As mentioned earlier, their opening characteristics are not significantly different in spite of their fabric areal density difference in the canopy. Comparing the results in Figs. 8a and 8b, one can see that the correlation

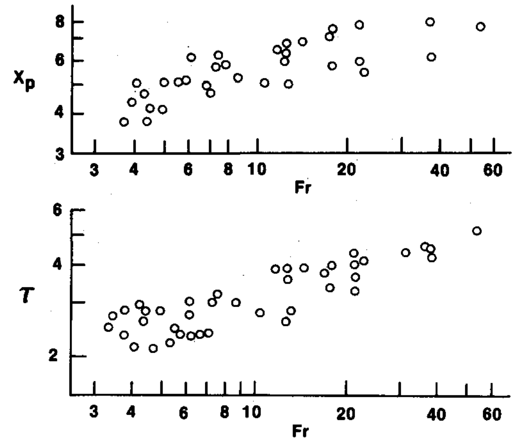


Fig. 10a Opening characteristics of 1.1 oz/yd² ¼-scale model C9 parachute for $M_r = 0.13$.

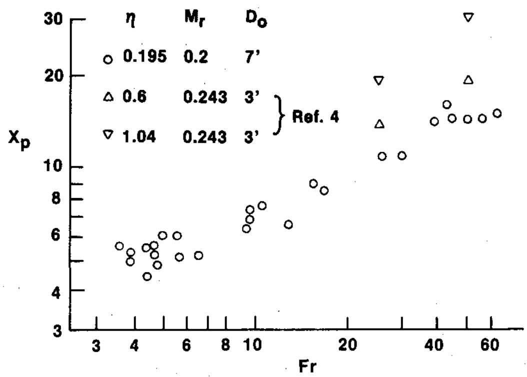


Fig. 10b Opening characteristics of 1.1 oz/yd² ¼-scale model C9 parachute.

between the full-scale and the ¼-scale C9's made from the same 1.1 oz/yd² nylon is not satisfactory (also shown in Fig. 3). Similarly, Fig. 8b shows that the correlation between the full-scale and the ¼-scale C9's made from the same 4.75 oz/yd² is also unsatisfactory and even worse than the correlation between the 1.1 oz/yd² ¼- and full-scale parachutes. Figure 8b also shows that the correlation between the 1.1 oz/yd² ¼-scale model C9 and the 4.75 oz/yd² full-scale C9 is not satisfactory.

Values of X_p and τ of the 10 and 14 oz/yd² full-scale C9's are shown in Fig. 9. Because of the less orderly opening of these heavy nylon parachutes, the data scatter is greater than that of the 1.1 oz/yd² light nylon C9, as indicated in Fig. 9. However, the correlation between the 10 and 14 oz/yd² full-scale C9's and the 1.1 oz/yd² ¼-scale C9 in Fig. 9 is better than those shown in Figs. 4 and 8, where 1.1 and 4.75 oz/yd² ¼- and full-scale C9's are compared. This improved correlation shows the importance of using lighter and less stiff canopy fabric for the models in parachute modeling. The actual fabric areal density ratio between the full scale and the ¼ scale is approximately 10. For a 1.1 oz/yd² full-scale parachute, this result projects that a 0.1 oz/yd² nylon is required for its ¼-scale models. Currently, such a light nylon is not available commercially, but it is needed to model full-scale parachutes realistically, which are commonly made of 1.1 oz/yd² nylon.

It is constructive to compare the aforementioned results with those obtained from the dimensional analysis conducted by Lingard[7] and Steeves.[14] Their results showed that the scaling of a parachute opening requires that the canopy fabric areal density ratio between the small-scale model and the full-scale parachute to be the same as the geometric ratio (¼ for the current investigation), and the porosity ratio to be the square root of the geometric ratio (½ for the current investigation). Based on the fabric areal densities in Table 1, their ratios between the ¼-scale model and the full-scale C9's are 1/4.4, 1/9.8, and 1/13 for the 4.75, 10, and 14 oz/yd² nylon fabrics, respectively. Therefore, the 1.1 and 4.75 oz/yd² nylon together most closely satisfy the required ¼ geometric ratio. However, as shown in Table 1, the air permeability or porosity value of the ¼-scale model is higher than that of the full-scale C9's, which is opposite to that required by the ½ geometric ratio. Therefore, the commercially available nylon fabrics do not satisfy the porosity requirement as determined by dimensional analysis. Therefore, direct comparison between the current results and the dimensional analysis is difficult; however, the following comparison provides some insight.

As shown in Fig. 8b, values of X_p and τ of the 1.1 oz/yd² ¼-scale model are higher and lower, respectively, than those of the 4.75 oz/yd² full-scale C9. If the air permeability of the 1.1 oz/yd² nylon decreases from 72.5 to 26.5 ft³/(min-ft²) to satisfy the ½ ratio requirement, the less porous canopy will result in shorter opening time or lower τ, and larger opening force or higher X_p. This behavior will result in less satisfactory correlation than the current results shown in Fig. 8b. Therefore, the current results do not seem to agree with the anticipated results based on the fabric areal density and porosity scaling requirements from dimensional analysis; new nylon fabrics, therefore, need to be developed for further investigation in parachute modeling.

Measurements at High Froude Numbers

The results and discussion so far have been focused on values of X_p around 5. In a typical airdrop operation, the X_p or the g force is usually less than 5. Higher g forces would cause damage to the payload and are obviously not desirable. To extend the data base for the current study, higher X_p values were obtained and shown in Fig. 10 at high Fr numbers for the 1.1 oz/yd² ¼-scale model C9. It is seen that X_p is proportional to Fr^c, where c is approximately 0.3 for $M_r = 0.13$, and 0.45 for $M_r = 0.2$. Also included in Fig. 10b are some data from the wind tunnel studies of Refs. 3 and 4 on a 3-ft-diam, 1.1 oz/yd², solid cloth model parachute. The M_r value in Refs. 3 and 4 was slightly higher than the current value of 0.2, and the 3-ft-diam model was stiffer than the current ¼-scale 7-ft-diam model as reflected in the η values. Consequently, the data in Refs. 3 and 4 are higher than the current ones, in particular, the stiff model with $\eta = 1.04$.

At high snatch velocities, the opening force is so high that it may be less affected by the stiffness of the canopy than at lower snatch velocities. Therefore, satisfactory correlation in X_p and τ between a full-scale parachute and its model may be obtained by using the same canopy fabric for both. The full-scale C9 data obtained by Berndt and DeWeese[1,2] and examined by Lee[13] tend to support this. However, more work and data at high Fr numbers are needed to confirm this result.

Conclusions

The current parachute modeling study has investigated the opening characteristics of full-scale and model solid cloth parachutes made from the same and different canopy fabrics. The differences in canopy fabrics included areal density and porosity. It was found that using a lighter fabric for the model gave better correlation with the full scale than using the same fabric as the full scale. However, further work needs to be done and new nylon fabrics need to be developed to model full-scale 1.1 oz/yd² parachutes realistically.

The following conclusions are made:

1) The Froude number and mass ratio are two important parameters for the nondimensional peak opening force and nondimensional opening time for modeling parachute opening This finding is consistent with the scaling result for parawing opening.[11,12]

2) Qualitative modeling results can be obtained if the canopy fabric used for the model is the same as that used for the full scale. However, better results are obtained if lighter fabric is used for the model to account for the problem of canopy stiffness.

3) A nylon much lighter than 1.1 oz/yd^2, preferably ¼ to $\frac{1}{10}$ of 1.1 oz/yd^2, is needed for model parachutes so that 1.1 oz/yd^2 full-scale parachutes can be realistically modeled. On the scaling of porosity, the current result and the requirement from dimensional analysis do not seem to agree. Therefore, the porosity of the new light nylon has to be varied, i.e., equal to, larger, and smaller than that of the 1.1 oz/yd^2 nylon so that the porosity effect can be experimentally investigated.

4) To eliminate outdoor wind effects and to decrease data scatter, a 300- to 400-ft-high enclosure with quiescent atmosphere, such as that used in parawing modeling,[11,12] would be useful for more closely controlled parachute opening tests and more exact comparison between models and full-scale parachutes.

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