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Controlled Opening Method for Clustered Parachutes

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This paper presents a method for achieving simultaneous opening of clustered parachutes. The method involves connecting and partially reefing the parachutes in a cluster during the initial stage of the opening so that they open together as a single parachute; they are then disconnected and disreefed at almost full inflation, thereby controlling and opening the parachute simultaneously. This method, called the controlled opening method, was tested with clusters of 64-ft-diam G-12 cargo parachutes, 100-ft-diam G-11 cargo parachutes, and 28-ft-diam C-9 personnel parachutes. Their openings were significantly improved when compared to the openings of these clusters without using the controlled opening method.

Introduction

CLUSTERED parachutes offer several advantages over a single large parachute. The important ones are shorter opening time and distance, easier fabrication and ground recovery, and more stable descent. The major difficulty of clustered parachutes is that parachutes in a cluster generally open randomly and unevenly; the random opening results in a large variation in opening times and an uneven distribution of opening forces among the parachutes. Consequently, the lead-opening parachutes are often damaged, resulting in an unsatisfactory airdrop operation.

In view of the importance of uniform opening of clustered parachutes, some fundamental studies of flowfields and opening of clustered parachutes were conducted by Braun and Walcott,[1] Heinrich and Noreen,[2] Heinrich et al.,[3] Wolf and Spahr,[4] and Nicuum and Kovacevic.[5] Current techniques for improved cluster opening are generally those used for controlling the opening of a single parachute. They include reefing the canopy skirt, adding a secondary chute at the skirt, introducing a pull-down centerline, and applying tension force at the apex by a drogue chute. These techniques generally modify the opening of a single parachute, but they do not necessarily improve the opening of a cluster as a whole. This is evidenced by the current problems in opening 100-ft-diam standard U.S. Army G-11 cargo parachute clusters[6] and the great difficulties in opening 137-ft-diam developmental cargo parachute clusters.[7,8] Most recently, Johnson[9] developed a central reefing/disreefing system that addressed the opening of a cluster as a whole. His system improved the opening of a cluster of three 52.5-ft-diam parachutes. This paper presents a method for improved opening of clustered parachutes. The method was tested extensively with clusters of various size and number of parachutes. Test results demonstrated that the method improves their opening significantly.

Concept and Method Development

Background and Concept

In a standard parachute cluster, each parachute is packed in its own deployment bag. When the parachutes are deployed, they come out of the bags and open individually and randomly. This is illustrated in Fig. 1, which shows the common lead- and lag-opening problem of clustered parachutes. This opening sequence clearly shows the random and uncontrolled inflation nature of clustered parachutes. The parachutes in Fig. 1 are 64-ft-diam flat circular, solid cloth, standard G-12 U.S. Army cargo parachutes. For larger parachutes, the inflation becomes worse, as indicated by Everett et al.[7] and Vickery et al.[8] in their attempt to use a cluster of six 137-ft-diam parachutes to recover a 60,000-lb payload. Wind-tunnel model studies of flowfields of clusters[5] showed that pressure and velocity distributions of a cluster are highly nonuniform. Such flow distributions coupled with individual curvilinear motion of each canopy in a full-scale cluster results in a highly unfavorable flowfield for uniform cluster opening. Nicuum and Kovacevic[5] suggested that important requirements for a uniform cluster opening are to avoid developing unsymmetrical flowfields around the cluster and to maintain symmetric geometry during opening. It appears that, if the air space between the canopies is eliminated by strategically connecting the canopies at the skirt during opening, the resultant flowfield should be similar to that of a single large parachute; inlet air velocity for each canopy will then be similar. Thus, a more symmetrical geometry and a more uniform cluster opening will be obtained.

In addition to the flowfield problem, the other problem is that large amounts of slack fabric of each canopy in a cluster flutter with no fixed pattern during opening, as shown in Fig. 1. This results in random filling of the canopies. If the amount of slack fabric is decreased during initial opening, to minimize random fluttering, the canopies should be tighter and the opening should be more positive. Standard skirt reefing decreases the slack fabric in the skirt area, but not necessarily the rest of the canopy above the skirt.

Based on these two desired features of connected and tight canopies, the following method was developed for improved cluster opening.

Description of Method

The method of connecting the canopies and decreasing the slack canopy fabric is illustrated in Fig. 2, using three parachutes (labeled as 1, 2, and 3) as an example (suspension lines are not shown for clarity). As shown in Fig. 2c, canopies 1 and 2 are partially reefed and connected along the skirt section OA. Skirt sections EFA and ABC of canopies 1 and 2, respectively, are not reefed. Similarly, canopies 2 and 3, and 3 and 1 are partially reefed and connected along the skirt sections OC and OE, respectively; skirt section CDE of canopy 3 is also not reefed. Since the three canopies are connected, they have to be packed in one single deployment bag. When they are extracted from the deployment bag during initial opening, they come out together as shown in Fig. 2a. They continue to inflate together as shown in Figs. 2b and 2c. Note

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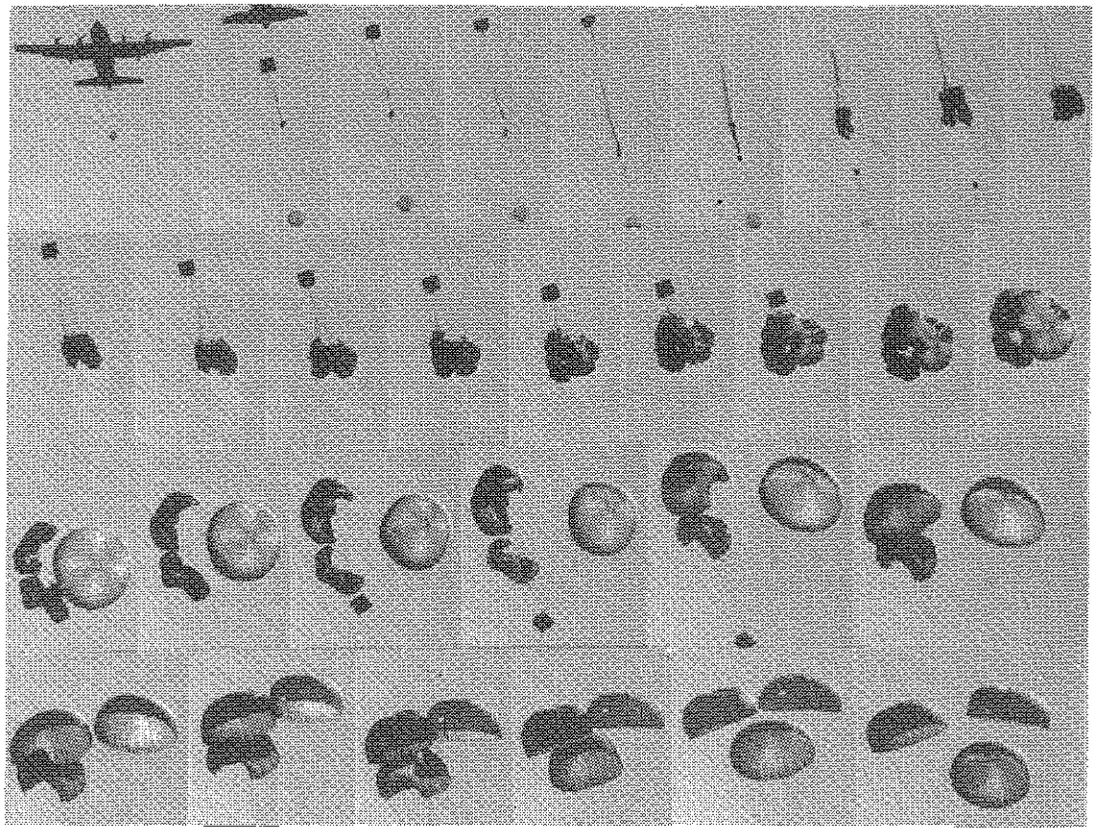

Fig. 1 Sequential photographs showing the opening of a standard three G-12 cluster.

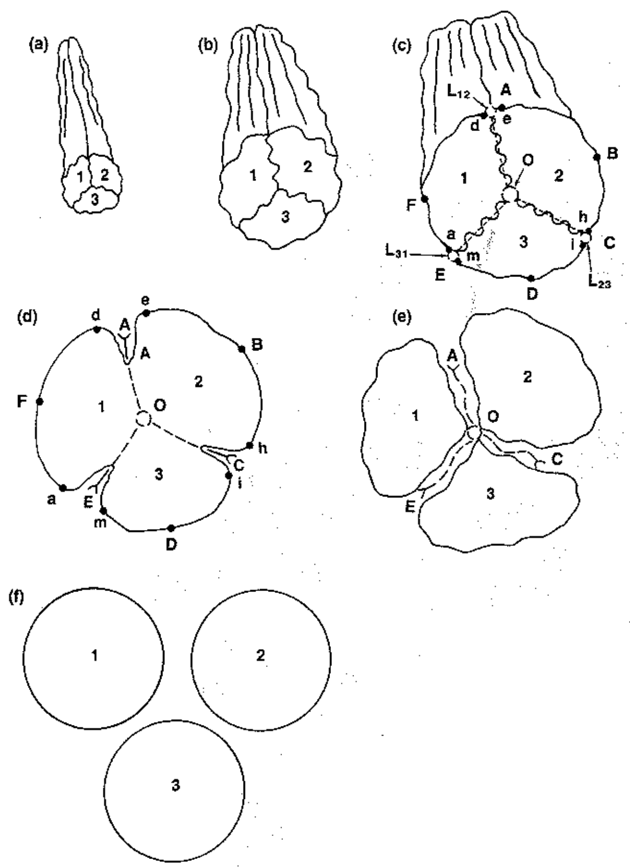

Fig. 2 Schematics showing the concept of the controlled opening method.

that the air space that occurs between the parachutes in a standard cluster has been eliminated.

The slack fabric of the three canopies is confined to the inside of the large single canopy formed by the three canopies 1, 2, and 3. The large single canopy is exposed to an improved flowfield and the three connected canopies are exposed to similar inlet air velocities for simultaneous opening. As the three parachutes continue to inflate, the opening forces in the skirt area break the connections at points A, C, and E, separating the three canopies, as shown in Figs. 2d and 2e. (Details of this controlled breaking and release mechanism for the canopies are shown in Fig. 3 and described later.) Finally, the three parachutes are fully inflated and separated, as shown in Fig. 2f.

Details of Fig. 2c and the mechanism that controls the reefing, connection, and release of the canopies are shown in Fig. 3. Canopies 1 and 2 are reefed and connected by the canopy control line OA through the n pairs of reefing rings from c to d for canopy 1, and f to e for canopy 2. Canopies 2 and 3, and canopies 3 and 1 are reefed and connected identically to canopies 1 and 2. The inner ends of the three control lines OA, OC, and OE are tied at the center, O, of the three canopies to the metal ring, R_o. The diameter of the ring R_o is larger than that of the reefing rings so that R_o will not slide through the reefing rings but stay at the center, O. At the outer ends of the lines OA, OC, and OE, line loops are used to tie the lines to the reefing rings; e.g., line loop L_{12} ties OA to reefing rings d and e as shown in Fig. 3. (Reefing line cutters can be used in place of the line loops, but they will be more complicated and expensive to use.)

As mentioned earlier, the tension force generated at the skirts during opening break the three line loops L_{12}, L_{23}, and L_{31}, thereby releasing the three control lines OA, OC, and OE as shown in Fig. 2d. The reefing rings then slide along the control lines OA, OC, and OE to separate the three

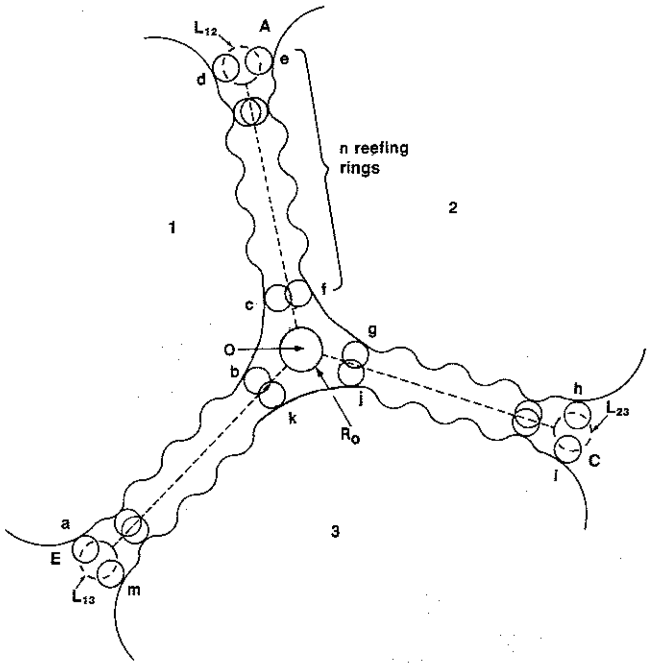

Fig. 3 Schematic showing the mechanism of the controlled opening method.

Table 1 Optimum variables for two G-12 cluster

Cluster	Canopy control line length, ft	Number of reefed gores on one control line (% of reefed gores)	Breaking strength of control line loop, lb
Two G-12	10	16 (32 per G-12 or 50%)	100

canopies as shown in Fig. 2e. Finally, the three canopies are fully inflated as shown in Fig. 2f.

To maintain symmetry during opening, the same amount of reefing, the same control line and length, and the same line loop are used for each parachute. These variables depend on the type of parachute, the number of parachutes in the cluster, and the deployment condition. By choosing the optimum combination of these variables, the opening of the cluster should be well controlled and more uniform. Thus, this method is called the controlled opening method.

Cluster Opening by the Controlled Opening Method

Two G-12 Cluster

The controlled opening method was first tested using a cluster of two G-12 parachutes. A deployment bag was made by modifying and connecting two G-11 parachute (same type as G-12, but larger with 100-ft-diam) deployment bags for the two G-12 cluster. Standard U.S. Army airdrop procedures for G-12 parachutes were used for the cluster tests; these included the 2200-lb design payload for each G-12 (4400 lb for the cluster) and the 15-ft-diam ring-slot drogue chute for payload extraction of 130-kt C130 aircraft speed. The only different procedure was that the two G-12s were rigged together by using the controlled opening method and packed in the one large deployment bag. For comparison purposes, some standard two G-12 cluster tests, i.e., each G-12 packed in its own deployment bag, were also conducted. In all of the tests, a load cell in the riser extension of each parachute and a telemetry system in the payload were used to measure the opening force F_o as a function of time t. Comparison of the two measured opening forces of the cluster would then show the degree of simultaneity of the opening.

Various values of the control variables were attempted for the two G-12 cluster. The variables that showed the best performance are shown in Table 1. Figure 4 shows the opening sequence of a two G-12 cluster using the controlled opening

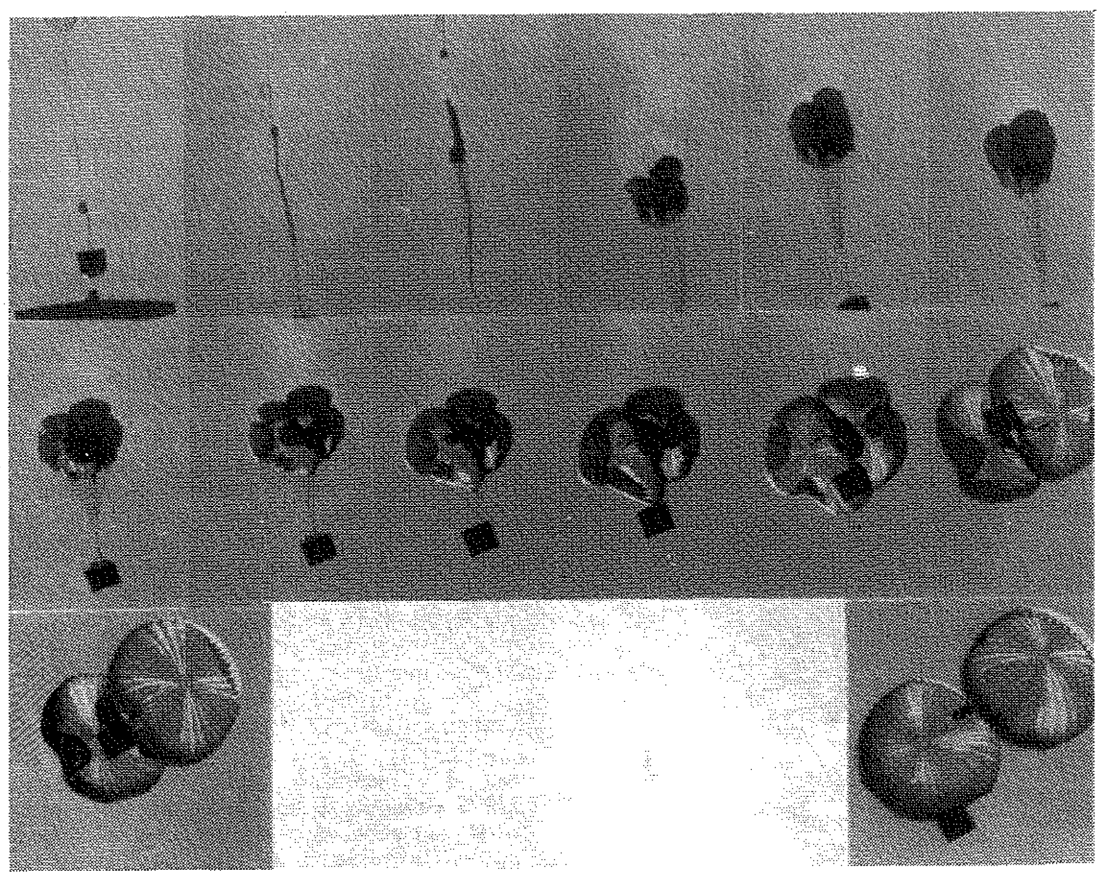

Fig. 4 Sequential photographs showing the opening of a two G-12 cluster using the controlled opening method.

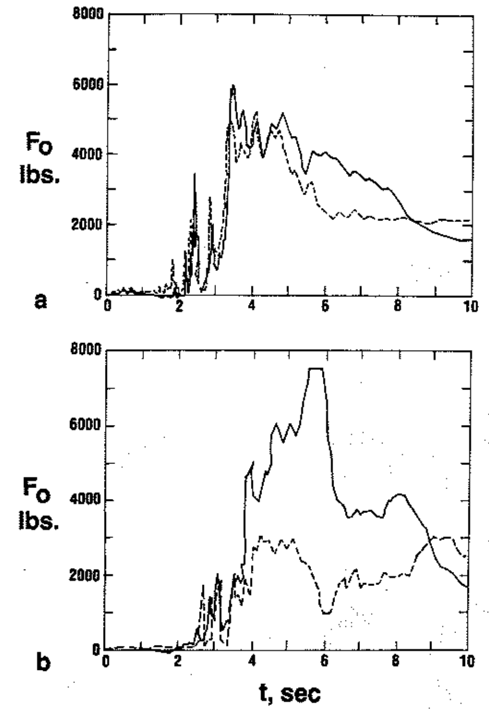

Fig. 5 Comparison of opening between two clusters of two G-12s: a) controlled opening method; b) standard method.

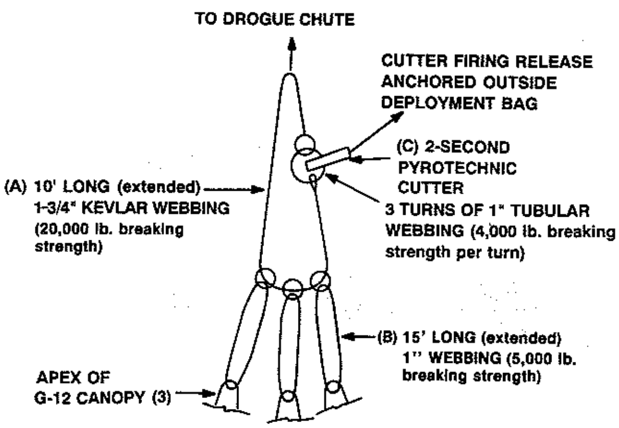

Fig. 6 Schematic of the apex attachment device.

method with the control variables just mentioned. As designed by the method, the two G-12s were held together during opening. The airspace between the two parachutes was eliminated and they inflated as though they were one parachute. When the two parachutes were almost fully inflated, the opening forces at the skirts broke the two control line loops and separated the canopies to complete the opening. This simultaneous opening is quantitatively shown by the measured opening forces in Fig. 5a. It is seen that shortly after canopy snatching at about 2.5 s, the two opening forces rose together, indicating the controlled and simultaneous opening. The simultaneous opening continued until the two control line loops broke. At this instant, the two G-12s were almost fully opened; the noncontrolled opening occurring thereafter had lower forces and was not critical.

Figure 5b shows the opening forces of a two G-12 cluster using standard packing procedures. It is seen that the opening was highly uncontrolled. Immediately after canopy snatch, one G-12 opened more quickly than the other one. This lead and lag opening persisted, resulting in the peak opening force of the lead-opening G-12 150% greater than that of the lag-opening G-12; whereas the peak opening forces in Fig. 5a are practically the same. Comparison between Figs. 5a and 5b

Table 2 Optimum variables for three G-12 cluster

Cluster	Canopy control line length, ft	Number of reefed gores on one control line (% of reefed gores)	Breaking strength of control line loop, lb
Three G-12	15	25 (50 per G-12 or 78%)	430

shows the significant improvement in the opening by the controlled opening method.

Three G-12 Cluster

The controlled opening method was further tested using a cluster of three G-12 parachutes. The three G-12 cluster was packed using the method and the same deployment bag used for the two G-12 cluster. A standard weight of 6600 lb was used. Opening tests were conducted at 130-kt deployment speed from a C130 aircraft.

High-speed movies of the opening tests showed that it was necessary to decrease the random flapping motion of the apexes of the canopies during canopy snatching and initial inflation (a common problem for clusters). An apex attachment device shown in Fig. 6 was developed to solve this problem. The device consists of a Kevlar loop (A in Fig. 6). One end of the loop is connected to the 15-ft-diam drogue chute and the other end is connected to the apexes of the three G-12s by three webbing loops (B). During canopy snatching and initial inflation, the drogue chute applies a tension force through the Kevlar loop to the three apexes, thereby keeping the three canopies from flapping. The three canopies are held together by the Kevlar loop until air starts to fill the apex areas and the three canopies begin to separate. The 2-s pyrotechnic cutter (C) is then fired to open the Kevlar loop, thereby releasing the three canopies to continue inflation. Numerous tests were conducted to determine the physical strength and dimensions of the apex attachment device and the delay time of the cutter. Those shown in Fig. 6 were found to work well.

Various control variables were also examined. Those that showed the best performance are shown Table 2. The opening of a three G-12 cluster from two tests using the controlled opening method is shown in Figs. 7a and 7b. Similar to the schematic in Fig. 2, the three parachutes were connected and held together from snatching to almost full inflation. The elimination of canopy flapping by the apex attachment device is clearly shown in the top row of the pictures in Figs. 7a and 7b. The airspace between adjacent parachutes was eliminated and the three connected canopies opened as one large parachute. The canopy fabric was tight without much slack, resulting in a positive and synchronized opening. Compared to Fig. 1, the significant improvement in opening provided by the current method is evident. The need for stiff canopy skirts[10] and controlled clusters[11] for improved cluster opening were emphasized in the literature. The current method provides both.

Comparison of the opening force distributions between a three G-12 cluster using the controlled opening method and a standard three G-12 cluster is shown in Fig. 8. It is seen that the opening of the standard three G-12 cluster was highly uncontrolled in that one parachute was subject to the majority of the total opening force, whereas the current method resulted in a much more even distribution of the total opening force among the parachutes.

Close examination of Fig. 8a reveals that the overall cluster opening behavior resembles that of a single parachute with one-stage reefing. Part I of the opening force profile in Fig. 8a corresponds to the time period when the three G-12s were connected and inflated together (like a reefed single parachute). Time t_r is the time when the three outside line loops at the skirts broke and the three canopies began to separate (like the cutter cuts the reefing line to disreef the parachute).

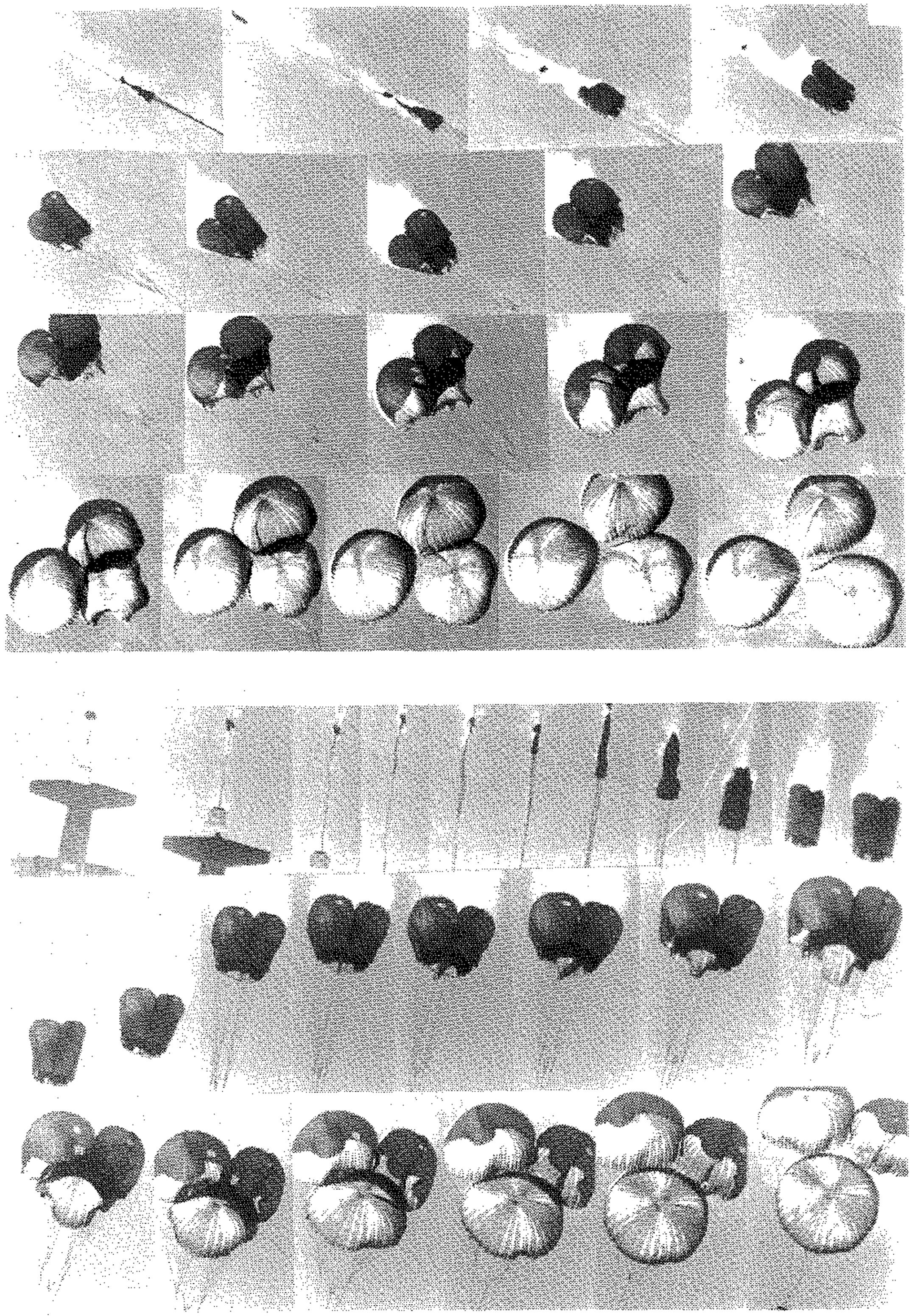

Fig. 7 Sequential photographs showing the opening of two tests of a three G-12 cluster using the controlled opening method.

Part II corresponds to the second or final stage of the cluster opening when the canopies were no longer connected (like a disreefed parachute). Based on the numerous three G-12 cluster opening tests, part I of the opening is consistently uniform. The initial opening force rise in part II is also uniform. However, in the latter part of part II, when the three parachutes are separated and inflate in an uncontrolled manner, the opening is not as uniform as that in part I. This overall behavior is quantitatively shown by comparing the percentages of the total opening force F_o experienced by the three G-12s; the calculated results based on Fig. 8a are shown in Fig. 9. In part I, the percentages converged to the ideal distribution of 33.3% toward time t_r, demonstrating the effectiveness of the controlled opening provided by the current method. After the three outside control line loops broke at time t_r, the percentages began to diverge from 33.3% in part II, indicating the uncontrolled nature of the opening.

Part I, the initial inflation phase of the cluster, is an important and critical part of the opening because it sets the stage for the subsequent opening in part II. If part I is not satisfactory, such as that shown in Fig. 8b, uniform opening of the cluster as a whole will be highly unlikely, as indicated in Fig. 8b. The more even opening force distribution in a cluster, such as that in Fig. 9, is satisfactory in terms of maintaining the structural integrity of the cluster. On the other hand, the nonuniform opening force distribution in Fig. 8b is highly susceptible to canopy structural damage.

Four and Eight G-11 Clusters

The controlled opening method was extended to a cluster of four larger G-11 parachutes. The G-11 is the largest standard U.S. Army cargo parachute and has a payload capacity of 3500 lb. G-11 clusters are currently used for heavy cargo airdrop.

A large deployment bag with dimensions of 1.5 ft (height) × 6 ft × 6 ft was made for a cluster of four G-11s. Because of the heavy total weight of approximately 1000 lb for the four G-11s, eight pieces of 0.5-in. 1000-lb breaking strength webbing equipped with cutting blades were tied across the bag to avoid early release of the four G-11s before line stretch.

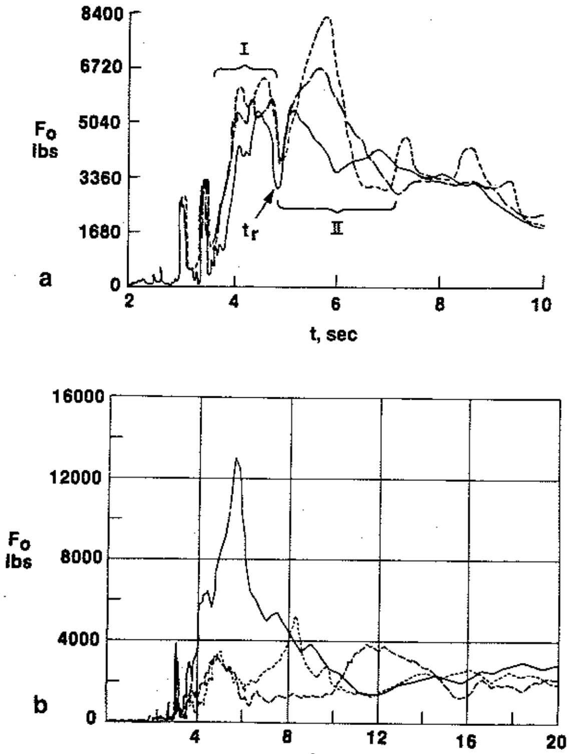

Fig. 8 Comparison of opening between two clusters of three G-12s: a) controlled opening method; b) standard method.

Canopy release after line stretch was ensured by cutting the eight 0.5-in. webbings using the blades that were activated during snatching by the riser clevises of the four G-11s. In addition, because of the bulk of the four connected canopies, webbing loops were sewn inside the deployment bag and used to secure the four canopies so that they would be deployed orderly.

Similar to the three G-12 cluster, flapping of the apex areas of the four G-11 cluster during initial opening also had to be suppressed. Instead of using an apex attachment device as shown in Fig. 6, a simpler 115-ft-long pull-down centerline (PDCL) was used for each G-11. The 115-ft length is 15 ft longer than the standard 100-ft PDCL used to pull down the vent area for higher canopy drag during steady descent. The 115-ft PDCL was used only to pull down the vent area to avoid canopy flapping during initial inflation when the canopy was elongated. This worked well, as will be shown later. This PDCL method is much simpler to use than that shown in Fig. 6 and should be used first, especially for large canopies.

Figure 10 shows the rigged four G-11 system secured to the platform. A standard 14,000-lb weight was used as the payload. Opening tests were conducted at 130-kt deployment speed from a C130 aircraft. The control variables shown in Table 3 were found to give the best performance.

Figure 11 shows a typical opening sequence of a four G-11 cluster using the controlled opening method. Similar to the three G-12 cluster opening in Fig. 7, the controlled, positive, and orderly opening of the four G-11s provided by the current method is evident. During initial opening (first two rows in Fig. 11), the 115-ft PDCLs effectively pulled down the vent areas to keep the canopies from flapping. The PDCLs along with the current method resulted in a positive and synchronized cluster opening. Canopy fabric was tight and stiff without much slack. Uniform opening continued until the four control line loops broke (middle of the third row in Fig. 11). The four partially opened canopies then separated to complete the opening. At full inflation, the PDCLs became loose as expected (last row in Fig. 11).

Two parts of opening separated by time t_r were also observed, as shown in Fig. 12. Part I corresponds to the opening phase when the four G-11s were connected, and part II corresponds to the opening phase after the four control line loops broke at time t_r to separate the four canopies. The percentage opening force distribution $\bar{F}_o$ is shown in Fig. 13. It is seen again that the percentages converged to the ideal distribution of 25% in part I toward time t_r, indicating the effectiveness of the current method. After t_r, the percentages diverged from 25% in an acceptable manner. The overall distribution is satisfactory and significantly better than that of a standard four G-11 cluster.

A cluster of eight G-11s is often used by the U.S. Army to airdrop 40,000-lb heavy cargoes. The current controlled opening method was further extended to two clusters of four

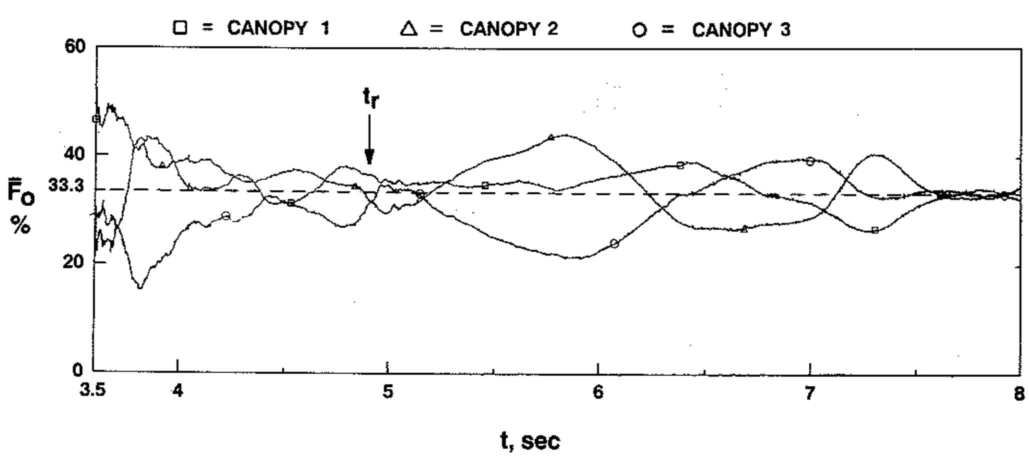

Fig. 9 Opening force distribution of a three G-12 cluster using the controlled opening method.

Fig. 10 Photograph showing a rigged four G-11 cluster using the controlled opening method (in one deployment bag).

Table 3 Optimum variables for four G-11 cluster

Cluster	Canopy control line length, ft	Number of reefed gores on one control line (% of reefed gores)	Breaking strength of control line loop, lb
Four G-11	30	50 (100 per G-11 or 83%)	600

G-11s to demonstrate the applicability of the method to eight G-11 heavy cargo airdrop. Only one test was conducted because of cost constraints. Consequently, the control variables in that test were not the optimum. Each cluster of four G-11s was rigged using the controlled opening method as described previously. One cluster was positioned on top of the other on the platform. During opening, the four G-11s of each cluster opened together, as expected. The two clusters or the eight G-11s also opened well together as a whole although the control variables were not the optimum. Figure 14 shows the opening force distribution $\overline{F}_o$ of the eight G-11s immediately after canopy snatch at t = 10.7 s. It is seen that the eight $\overline{F}_o$ values converged to the ideal distribution of 12.5% up to time t = 13 s when the eight outside control line loops broke; $\overline{F}_o$ then began to diverge when the eight G-11s were separated. Such $\overline{F}_o$ distribution shows the controlled nature of the opening, thereby demonstrating the applicability of the current method for eight G-11 heavy cargo airdrop.

Three C-9 Cluster

The controlled opening method was also tested using a cluster of three smaller C-9 personnel parachutes (28-ft-diam flat circular, solid cloth). Three C-9 parachutes were packed together using this method in one G-12 deployment bag. Opening tests were conducted with a 500-lb payload at 130-kt deployment speed from a C130 aircraft.

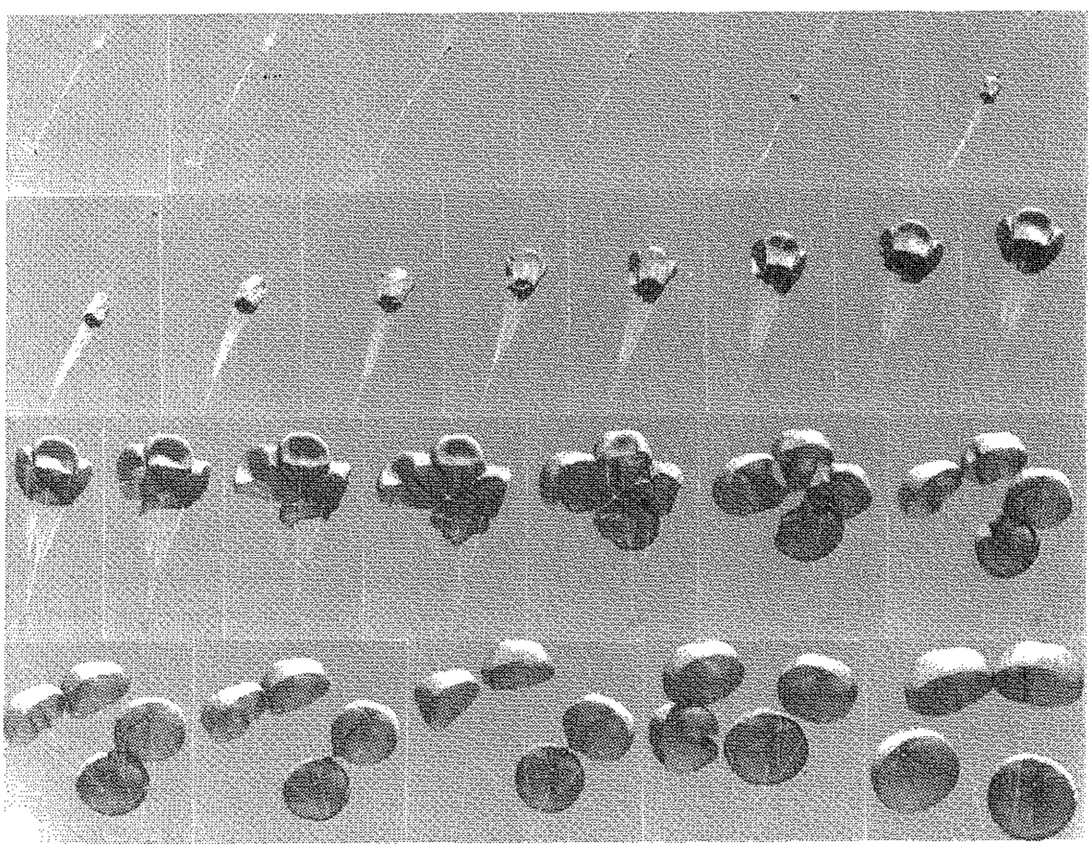

Fig. 11 Sequential photographs showing the opening of a four G-11 cluster using the controlled opening method.

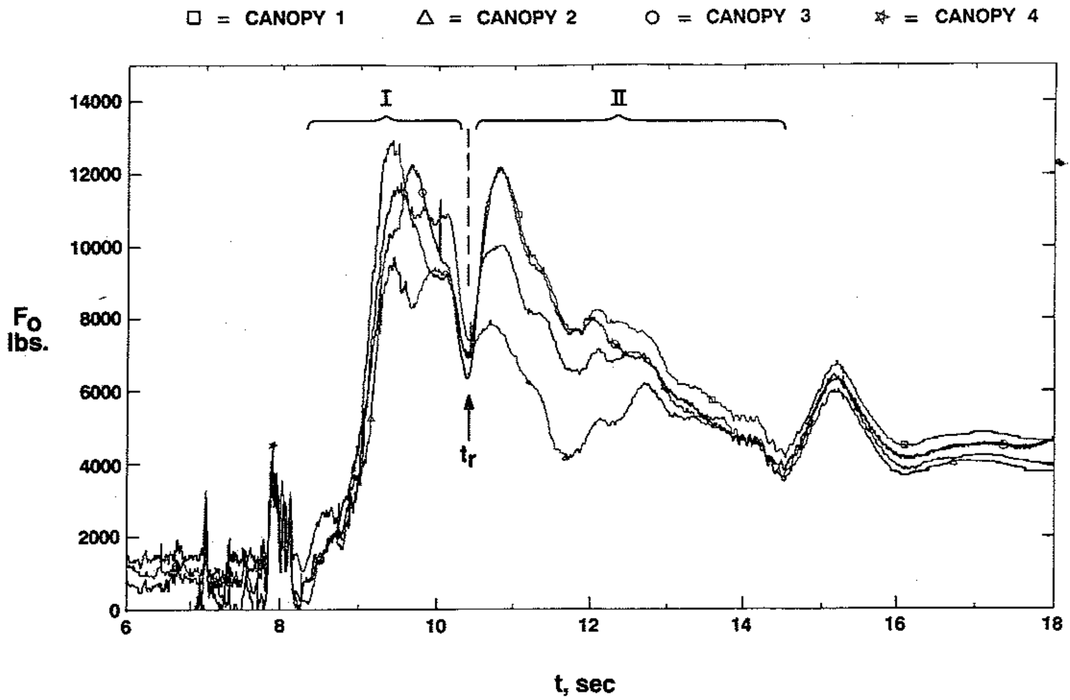

Fig. 12 Opening force measurements of a four G-11 cluster using the controlled opening method.

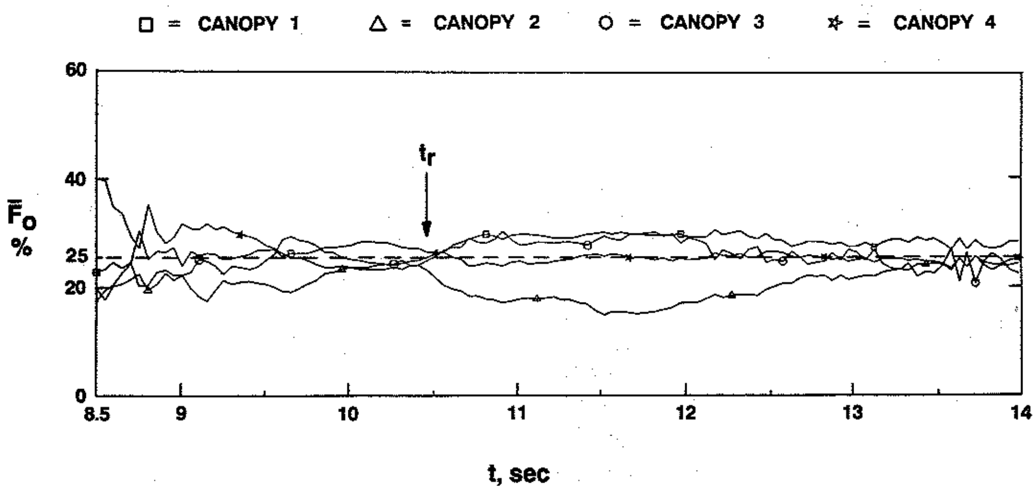

Fig. 13 Opening force distribution of a four G-11 cluster using the controlled opening method.

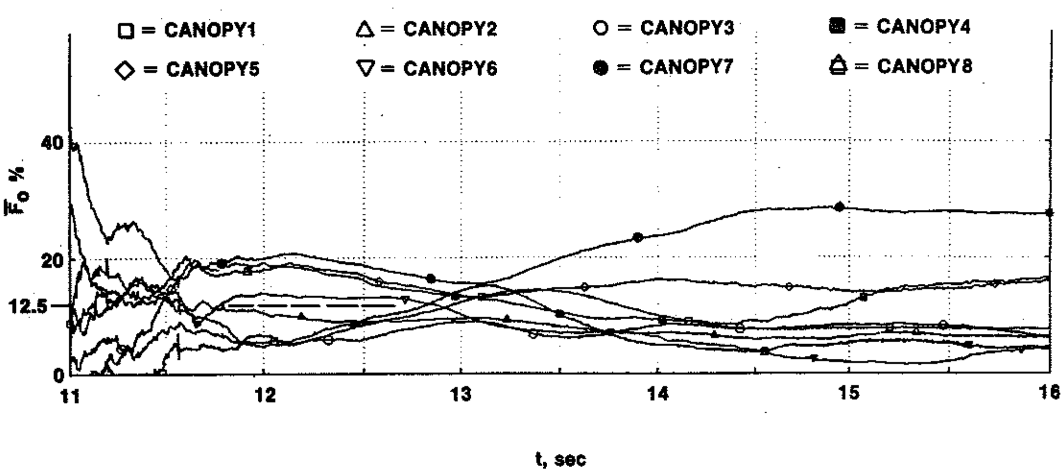

Fig. 14 Opening force distribution of eight G-11s (two clusters of four G-11s) using the controlled opening method.

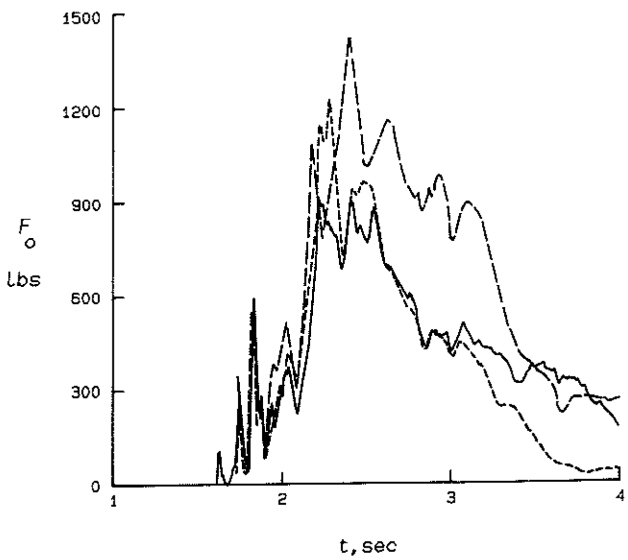

Fig. 15 Opening force measurements of a three C-9 cluster using the controlled opening method.

The measured opening forces of the three C-9s shown in Fig. 15 indicate that the overall cluster opening was satisfactory. The initial rise of the three opening forces (the initial opening) was simultaneous. When the three parachutes were separated, the opening forces were moderately different. The overall opening force distribution was satisfactory. Therefore, the current controlled opening method should also be applicable to clustered personnel parachutes.

Summary and Conclusions

A controlled opening method for improved opening of clustered parachutes has been presented (also see Ref. 12). The method includes partial reefing of the canopies in a cluster and connecting them together during most of the opening, and then separating them to complete the opening. In doing so, the canopies become symmetrical and stiff, thereby enabling the filling process to be more uniform among the canopies. This method was tested with two G-12, three G-12, four G-11, eight G-11 (2 clusters of four), and three C-9 parachute clusters. Their opening showed significant improvement when compared to the opening of the clusters without using this method. In particular, the current method consistently provides simultaneous opening of the parachutes during the critical initial inflation time period. This establishes the validity of the concept that connecting the parachutes together and inflating them together as one parachute does improve cluster opening.

The current method is flexible in that the amount of skirt reefing, the control line length, and the breaking strength of the control line loops can be varied to satisfy the requirements for simultaneous opening of clusters of different parachutes. Although extensive data of these three variables have not been obtained, the current test data indicate the following guidelines:

1) The breaking strength of the control line loop is within 10% of the peak opening force of each parachute in the cluster.

2) At least 50% of the gores of each canopy is reefed. The percentage increases as the canopy diameter and number of canopies increase.

3) The control line length is approximated by the radius of the circle formed by the inflated unreefed gores of all of the canopies in the cluster.

These guidelines should serve as the basis for initial selection of the three control variables. They can then be refined as testing progresses.

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