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A Novel CFD/Structural Analysis of a Cross Parachute

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Abstract

A novel CFD/structural analysis was performed to predict functionality of a cross parachute under loadings near the structural limits of the parachute. The determination of parachute functionality was based on the computed structural integrity of the canopy and suspension lines. In addition to the standard aerodynamic pressure loading on the canopy, the structural analysis considered the reduction in fabric strength due to the computed aerodynamic heating. The intent was to illustrate the feasibility of such an analysis with the commercially available software PATRAN, ABAQUS/Explicit, and Rampant.

I. Introduction

A CFD/structural analysis of a cross parachute was performed to predict parachute functionality and to illustrate the feasibility of such an undertaking with commercially available software. The commercial software packages PATRAN,¹ ABAQUS/Explicit,² and Rampant³ were used in the analysis. The determination of parachute functionality was based on the computed structural integrity of the canopy and suspension lines. In addition to the standard aerodynamic pressure loading on the canopy, the structural analysis considered the reduction in fabric strength due to the computed aerodynamic heating. Two Mach number conditions were chosen to test the structural limits of the parachute, and two different fabrics were analyzed.

The parachute under consideration is a traditional cross with dimensions indicated in Figures 1 and 2 (not to scale). The shape was chosen to extend the modeling

capability of the Rampant portion of the analysis since a solid canopy parachute and a ribbon parachute were already being examined. This type of parachute is used for a wide range of applications. Canopies fabricated from 2.25 oz/yd² nylon cloth and from 3 oz/yd² Kevlar cloth, with 200 lb braided nylon suspension lines, were analyzed. The procedure was to mesh the parachute with the geometry modeling and meshing code PATRAN, subject it to an approximate pressure loading with the structural analysis code ABAQUS/Explicit to generate a shape, use the shape in the Computational Fluid Dynamics (CFD) code Rampant to find the surface pressure and temperature distributions, and finally, use ABAQUS/Explicit to determine the parachute's structural response under the new pressure distribution.

II. Parachute Geometry

A full-open canopy geometry was required prior to conducting the CFD analysis. PATRAN was used to construct an initial shape and surface mesh of the cross parachute. Utilizing empirically based knowledge of the approximate shape of a fully inflated cross parachute canopy, the outer quadrant panels were angled from the flat position at 45 degrees, thereby minimizing the necessity for damping the canopy during the dynamic simulation. The resulting initial parachute geometry and superimposed mesh, generated by PATRAN, are shown in Figure 3. This mesh, in conjunction with nylon material properties and an estimated pressure differential on the parachute canopy, were utilized by ABAQUS/Explicit to define the deformed canopy shape. Based on considerations of stagnation pressure through a normal shock (an approximation since the bow shock is not precisely normal) and the low wake pressure intuitively expected on the external surface of the canopy, the canopy pressure differential was estimated to be 31 kPa, and was further assumed to be applied to the entire interior surface of the canopy.

The deformed canopy geometry and suspension lines computed by ABAQUS/Explicit are shown in Figure 4. Of particular interest is the observation of the small

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curvature at the center (or vent edge) of the canopy (a result of the fabric stiffness caused by the two panels overlapping) and the large curvature at the tips (or skirt edge) of the outer panels (the physical compromise between the radial pressure force exerted on the canopy and the stiff suspension lines which constrain the radial motion of the canopy). It should be noted that the deformed canopy shape shown in Figure 4 was extracted from the dynamic simulation at 50 ms after initial inflation. A slight plastic strain was incorporated into the material definition of the suspension lines, thereby damping the large oscillations observed during the early (20 ms) inflation animation which resulted in the quasi-steady deformed geometry presented in Figure 4. The slight extension of the suspension lines due to the implementation of the plastic strain is considered of no consequence during this phase of the analysis since the primary objective is to define the deformed geometry of the canopy.

An intermittent step prior to engaging the CFD analysis on the deformed canopy geometry was necessary. As can be observed in Figures 3 and 4, ABAQUS/Explicit utilizes 4-node quad elements to model the membrane structure, while the CFD code requires triangularization of the surface. This inconsistency was resolved by reading the deformed mesh back into PATRAN and converting each quad element into two triangular elements. The deformed canopy surface mesh for the CFD analysis is shown in Figure 5.

III. CFD Analysis

The CFD code Rampant was used to solve for the surface pressures and temperatures on the deformed canopy geometry shown in Figure 5. A time-accurate, compressible, laminar Navier-Stokes analysis was conducted for a Mach 4 simulation. The time-accurate simulation was necessary, based on the inherent unsteady nature of the wake generated by the bluff body geometry of the cross parachute. The negative aspect of the time-accurate simulation for an explicit code is the CFL constraint which limits the time step for this particular simulation to approximately 1 microsecond. Consequently, after 50,000 iterations, the simulation has progressed only 0.05 seconds, which may be insufficient time to establish the quasi-steady behavior of the upstream flowfield. Therefore, the results presented in this document may not capture the localized effects of the flowfield, but certainly represent a viable engineering solution to the desired surface temperature and pressure results on the deformed canopy.

A. Mach 4 Analysis

Figure 6 displays a magnified centerline cut-plane view of the flowfield in close proximity to the cross

parachute canopy (which has been overlayed for reference). The salient features of the flowfield are the strong bow shock which resides very close to the leading edge of the canopy, the relatively large wake region downstream of the canopy, and the expected asymmetry of the flowfield, which is substantiated by the velocity vector plot. It is difficult to assess the large magnitude velocity vectors in the near-field wake region based on a single cut-plane view, but it is hypothesized that the high velocity results from the air flow jetting through the slots between the quarter panels and accelerating into the low-pressure region associated with the near-field wake. Additional solution fidelity could be obtained through grid adaption, however, this technique was not implemented during this simulation due to time considerations.

The cross parachute canopy internal and external surface pressures are displayed in Figures 7 and 8, respectively. Certainly the most prominent aspect of the surface pressure shown in Figure 7 is the asymmetry of the distribution. While this asymmetry is invariably present (due to the unsteady nature of the problem), the magnitudes have stabilized at the current values, although the spatial distribution is transient. The rationalization for the transient, asymmetric nature is threefold: (1) the flowfield is inherently unsteady in the wake region due to the asymmetric vortex shedding; (2) the flowfield may not have achieved the quasi-steady convergence upstream of the canopy due to insufficient run time; and (3) the relatively coarse grid associated with the deformed canopy may be insufficient to resolve significant flowfield characteristics. It has been observed during the simulation, for example, that the high pressure bubble on the internal canopy surface is diminishing in size and relocating on the surface. Also, the higher pressure regions appear to be advancing into the outer quadrant panels as the simulation progresses.

As a final comment on the internal pressure distribution, consider that the maximum magnitude of the canopy surface pressure distribution, as calculated by RAMPANT, is 38 kPa (or 35 kPa assuming the imminent demise of the high pressure bubble). Recall that the original inflation analysis employed a uniform pressure distribution of 31 kPa to calculate the deformed canopy shape for the CFD analysis. While a rigorous investigation would demand an iterative process between the CFD and inflation analyses, the calculated pressures were assessed to be sufficiently close to the estimated value that an iterative process would introduce only secondary effects which are inconsequential compared to the assumptions and associated errors for the combined analyses.

The external surface pressure distribution for the cross parachute canopy is displayed in Figure 8. As observed, this distribution is relatively uniform, with the majority of the surface area experiencing a pressure magnitude which is a factor of 200 less than the *average*

internal pressure magnitude. As a final observation, note that there exists virtually no pressure differential across the edges of the quarter-panel slots (this requires comparison of the pressure magnitudes for the internal and external canopy surface pressures from both Figures 7 and 8). This deficiency of a pressure differential at this location would result in a lack of tension in the fabric. The result would be a phenomenon referred to as flutter damage, which has been documented for parachutes in supersonic flowfields and was observed during the structural analyses simulation animation.

Of primary concern for the Mach 4 case was the aerodynamic heating on the cross parachute canopy. Not only is the melt temperature of nylon relatively low at 522°K, but the fabric will lose significant strength at much lower temperatures, as discussed in the structural analysis section. Figure 9 shows the canopy internal surface temperature distribution for the Mach 4.0 simulation. The maximum surface temperature located at the tips (skirt) of the canopy are non-physical, since the magnitudes exceed the stagnation temperature for this flowfield. However, it has been observed, similar to the high pressure bubble discussed in Figure 7, that the high temperature regions are diminishing in size as the simulation progresses. Hence, the upper bound of 904°K appears reasonable (since this is slightly less than the stagnation temperature of 915°K), and the majority of the structure has a temperature in excess of 750°K. The obvious conclusion is that the nylon canopy would melt very rapidly after deployment, and would certainly not provide a viable decelerator. The same conclusion would apply to the cross parachute constructed from Kevlar, since the maximum temperature of 750°K exceeds the Kevlar decomposition temperature of 700°K, and the zero strength temperature of 728°K.

B. Mach 3 Analysis

Since the aerodynamic heating of the cross parachute canopy for the Mach 4 case deployment conditions resulted in surface temperatures which exceeded the melt temperature of nylon and the zero strength temperature of Kevlar, an analysis to determine structural integrity was superfluous. Consequently, a Mach 3 analysis (at a 10 km lower altitude) was undertaken. Figure 10 displays a magnified centerline cut-plane view of the flowfield for the Mach 3 CFD analysis. The notable characteristics of the flowfield are analogous to those identified for the Mach 4 case, with the appropriate reduction in dependent variable magnitudes.

The cross parachute internal and external surface pressures for the Mach 3 case are displayed in Figures 11 and 12, respectively. The canopy internal surface

pressure distribution is again observed to be asymmetric and exhibits similar transient nature with respect to the spatial distribution of the high pressure regions. The canopy external surface pressure distribution is noted to be highly symmetric, although slightly less uniform than the Mach 4 case. Unlike the Mach 4 case, the difference in magnitude between internal and external pressures is not a factor of 200, but more on the order of 10 to 60. The final pressure differential to be used for the structural numerical simulation was calculated based on the values presented in Figures 11 and 12, incorporating an extrapolation of the pressure magnitude trends observed during the unsteady simulation.

The canopy internal surface temperature distribution for the Mach 3 case is shown in Figure 13. As expected, the aerodynamic heating for this simulation is significantly less than the Mach 4 case. Similar to the Mach 4 case, the maximum temperature is non-physical since it slightly exceeds the freestream stagnation temperature. However, a check of the actual surface temperatures (with the smooth-filled or blending option disabled) revealed the small surface area which actually exceeds stagnation temperature. Again, this anomaly could be resolved with additional simulation time and grid refinement. Based on the relatively uniform distribution of the results shown in Figure 13 and bounding the upper limit by the freestream stagnation temperature, the canopy surface temperature was assumed to be a homogeneous 373°K (100°C) for the Mach 3 case.

IV. Structural Analysis Description

The structural analysis of the cross parachute was performed using the finite element code ABAQUS/Explicit with the results of the CFD analysis. This code uses an explicit algorithm to determine the dynamic response of structures, which also permits it to resolve the large deformation response necessary for this particular application. The model used for this analysis is the same model defined previously for the preliminary inflation analysis which determined the deformed shape for the CFD analysis. This model was displayed in Figure 3, and is utilized in ABAQUS/Explicit to define the initial geometry of the structure.

Analogous to the standard construction technique employed in fabricating cross parachutes, the canopy is modeled as two rectangular sections of cloth which are orthogonally overlapped at the center as depicted in Figure 14. Membrane elements are used in ABAQUS/Explicit to model the canopy cloth structure. Since the analysis uses an orthotropic material behavior to model the cloth response, two separate layers of membrane elements are used in the center overlap region, with the cloth warp direction aligned as indicated in Figure 14.

The standard construction technique employed for attaching *continuous* suspension lines to a cross

parachute canopy was used for this analysis. That is, the suspension lines, which are nominally 72 cm in length, are attached to the canopy by stitching the center 30 cm of the suspension line along the length (30 cm side) of the fabric rectangle, with the two free ends (each 21 cm in length) of the suspension line joined at the confluence (attachment) point. This is modeled by using common nodes for the fabric constituents which are overlapped at the locations of the applied stitching, and represents a valid model assuming the stitching does not fail. The suspension lines (which are also displayed in Figure 3) are modeled in ABAQUS/Explicit with bar elements. The canopy fabric originally was modeled as the 2.25 oz/yd² nylon. However, since the nylon fabric may not possess sufficient structural capacity after exposure to the aerodynamic heating, a 3 oz/yd² Kevlar fabric was also considered in the structural simulation. The correlation between the nylon and Kevlar fabric results will be discussed in the next section. The material constants used for the nylon and Kevlar fabric are summarized in Table 1.

Table 1: Material Behavior Description

Component	E _{warp} MPa	E _{fill} MPa	Poisson's Ratio	Failure Stress
Kevlar Cloth	8481	8481	0.1	423
Nylon Tape & Cloth	827	827	0.174	183

As determined by the CFD analysis, the surface temperature of the entire canopy was established at 373°K. Therefore, based on data obtained during high-strain rate tensile testing of fabrics at cold, nominal and hot temperatures (conducted in December 1992, to be published), nylon will experience a 30% decrease in tensile strength at 373°K, while Kevlar experiences a 10% decrease in tensile strength at 373°K. Therefore, the structural load capacity values listed in Table 1, adjusted to reflect the aforementioned reduction in tensile strength at 373°K, should be 380.7 MPa (55,215 psi) for the Kevlar cloth, and 128 MPa (18,580 psi) for the nylon tape and cloth.

A. Structural Analysis

The preceding section established the parachute model (initial geometry and mesh) and the material property characteristics for the structural analysis simulation. Hence, only the determination of the pressure loading is required to initiate the simulation.

As stated previously, the pressure distribution was obtained as a composite differential of the CFD results

incorporating extrapolated trends observed during the transient CFD simulation. This composite distribution was analytically fit to the Patran geometry using the data at 16 points across each of the five rectangles of the parachute. This pressure fit, which is displayed in Figure 15, then loads each element with the centroidal pressure values found in the model.

The structural analysis performed by ABAQUS/Explicit using the pressure distribution defined in Figure 15 applied on the initial geometry shown in Figure 3 resulted in the deformed shape and stress distribution (along the x-direction) displayed in Figure 16. This deformed shape does not characterize the final steady state geometry of the cross parachute, but represents the shape at a particular instant in the structural analysis simulation when the peak stresses occur. As observed, the peak stress in the canopy is approximately 93 MPa (13,500 psi), and this occurs in a very localized region adjacent to the attachment location of one of the suspension lines. Likewise, the peak stress which occurs in the suspension lines is less than 27.6 MPa (4000 psi).

Based on the magnitudes of the calculated peak stresses, the cross parachute should preserve structural integrity. That is, the peak stress would load a canopy constructed from the 3 oz/yd² Kevlar fabric to approximately 24% of capacity, while a canopy constructed from the 2.25 oz/yd² nylon fabric would load to approximately 73% of capacity. Similarly, the suspension lines would load to approximately 22% of capacity at peak stress.

B. Structural Analysis Summary

Load capacities were assessed in the canopy and suspension lines comprising the cross parachute using the calculated peak stresses for the increased dynamic pressure deployment conditions and empirical data obtained during high-strain rate fabric testing conducted at hot temperatures. The structural analysis determined peak magnitudes of 24% and 73% of load capacity in the canopy fabricated from 3 oz/yd² Kevlar and 2.25 oz/yd² nylon fabric, respectively. The analysis also determined the nylon suspension lines experienced a load equivalent to 22% of capacity at peak stress.

V. Conclusions

A cross parachute was analyzed to assess functionality at described deployment conditions. Aerodynamic pressure loading and canopy surface temperatures were determined from a CFD analysis conducted on a steady state inflated profile of the cross parachute canopy. These conditions were then applied in the structural analysis to calculate peak stresses in the canopy and the suspension lines. Functionality was assessed based on the structural integrity of the canopy and suspension lines.

The analysis results indicate that the cross parachute would survive and function as a viable decelerator during a Mach 3 deployment. This assessment is valid for a canopy fabricated from either the 2.25 oz/yd² nylon or the 3 oz/yd² Kevlar fabric.

VI. References

1. PATRAN 2 User's Manual, Version 2.5, PDA Engineering, Costa Mesa, CA, 1991.
2. ABAQUS/Explicit User's Manual, Version 5.2, Hibbitt, Karlsson, and Sorensen, Inc., Pawtucket, RI, 1992.
3. Rampant User's Guide, Version 1.0, Fluent Inc. Burlington, VT, 1992.

Figure 1. Cross Parachute Canopy Positioned Flat

Figure 2. Inflated Cross Parachute Depicting Suspension Line Length

Figure 3. Initial Geometry and Surface Mesh of

Figure 4. Deformed Canopy and Suspension Lines From the ABACUS/Explicit Simulation

Figure 5. CFD Surface Mesh of Deformed Canopy Geometry

Figure 6. Magnified View of Flowfield in Close Proximity to Cross Parachute Canopy at Mach 4 (m/s)

Figure 7. Cross Parachute Canopy Mach 4 Internal Surface Pressures (Pa)

Figure 9. Cross Parachute Canopy Mach 4 Internal Surface Temperatures ($^{\circ}\text{K}$)

Figure 8. Cross Parachute Canopy Mach 4 External Surface Pressures (Pa)

Figure 10. Magnified View of Flowfield Surrounding Canopy for Mach 3 Case (m/s)

Figure 11. Cross Parachute Canopy Mach 3 Internal Surface Pressures (Pa)

Figure 12. Cross Parachute Canopy Mach 3 External Surface Pressures (Pa)

Figure 13. Cross Parachute Canopy Mach 3 Internal Surface Temperatures ($^{\circ}\text{K}$)

Figure 14. Cross Parachute Construction Depicting Fabric Warp Direction

Figure 15. Spatial Distribution of Pressure Applied in Structural Analysis (psi)

Figure 16. Deformed Shape and Stress Distribution for Cross Parachute (psi)

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