

Supersonic Parachute Inflation Simulations Relevant To The Mars Sample Retrieval Lander

Francois Cadieux* and Michael F. Barad†
NASA Ames Research Center, Moffett Field, CA, 94035

The Mars Sample Return - Sample Retrieval Lander (MSR-SRL) mission goal was to land a rover on the Martian surface to collect soil samples left by Perseverance with intention of bringing them back to Earth for analysis. SRL design leveraged the heritage architecture, design, and hardware of the Mars 2020 mission as much as possible. However, the SRL mission planned to deploy the supersonic parachute at higher Mach and dynamic pressure. The parachute system used on Mars 2020 was certified for flight during the third ASPIRE (SR03) terrestrial flight test. SR03 deployed its parachute at a higher dynamic pressure than is planned for SRL, but at a significantly lower Mach number. We seek to reduce risk by determining whether SRL peak loads fall below those of SR03, which could help to qualify the parachute system without the need for further flight tests. We perform a fluid-structure interaction simulation of the Mars 2020 supersonic disk-gap-band parachute deployment under Mars 2020 conditions and compare predictions with the recorded flight data. We then simulate the same Mars 2020 vehicle and parachute system at higher Mach and dynamic pressure to predict the increase in peak loads. The predicted peak loads remain within the envelope of those tested by SR03. More analysis is needed to determine whether the maximum strains also remain below SR03 levels.

I. Nomenclature

M	Mach number
q	dynamic pressure (Pa)
V	velocity magnitude (m/s)
α	angle of attack ($^{\circ}$)
β	side slip angle ($^{\circ}$)
S	surface area (m^2)
S_{proj}	projected surface area (m^2)
F_{chute}	reconstructed parachute aerodynamic force (N)
F_{pull}	pull force (N)
F_{aero}	aerodynamic force (N)

II. Introduction

NASA and the European Space Agency created the Mars Sample Return (MSR) program to bring back samples of Martian material back to Earth [1]. The Mars Sample Retrieval Lander (SRL), once on the surface of Mars, would retrieve the samples collected and cached by the Perseverance rover. It would then launch these samples into Mars orbit where they would be captured and returned to Earth by another spacecraft. The MSR program was put on pause in November 2023 due its cost and complexity. It is at now risk of being canceled as of January 2026. Although the status of MSR-SRL is unclear, analyzing SRL parachute performance will still benefit future high mass / large payload delivery to the Martian surface. SRL's planned entry, descent, and landing architecture directly follows the Mars 2020 mission that landed Perseverance on February 18, 2021. SRL leveraged the proven architecture, design, and hardware of the Mars 2020 mission as much as possible to reduce cost and mission risk. Apart from modest changes to the aeroshell,

* Aerospace Engineer, Computational Aerosciences Branch, M/S 258-2, francois.cadieux@nasa.gov.

† Aerospace Engineer, Computational Aerosciences Branch, M/S 258-2.

the critical question is whether the Mars 2020 parachute system would be safe for SRL. The Mars 2020 parachute system was certified for Martian flight through two terrestrial flight tests as part of the Advanced Supersonic Parachute Inflation Research Experiment (ASPIRE) campaign dubbed SR02 and SR03 [2]. The peak recorded parachute force from the final flight test (SR03) was approximately 300 kN. SR03 was successful and only minor damage was observed on the recovered chute, so we can expect the Mars 2020 parachute system to perform well up to and including this peak load. By contrast, the Mars 2020 mission recorded a maximum parachute force of approximately 152 kN. This is because the parachute reached the line stretch stage at more benign atmospheric conditions and lower velocity and because of the significant momentum deficit caused by the wake of the 4.5 m diameter aeroshell upstream of the canopy.

Table 1 Comparison of freestream conditions at line stretch and peak parachute force for the Mars 2020 parachute system. [2, 3].

	q (Pa)	M	V (m/s)	$\max(F_{\text{chute}})$ (kN)
SR02	744.6	2.00	636.4	248.96
SR03	1028.4	1.88	584.7	299.53
Mars 2020	518.7	1.80	411.9	152.34
Mars SRL	882.9	2.38	518.8	N/A

The parachute deployment conditions for Mars SRL are planned to be at higher Mach number, dynamic pressure and velocity magnitude than Mars 2020: see Table 1 for detailed comparisons. Mach number aside, SRL’s parachute deployment dynamic pressure and velocity are slightly lower in magnitude than SR03, and it will benefit from the significant wake momentum deficit caused by the aeroshell. Verifying whether SRL peak loads exceed SR03 levels is critical for determining whether a new parachute is required.

Fluid-structure interaction (FSI) simulations for supersonic parachute inflation dynamics have made tremendous progress in recent years toward validating their predictions with experimental and flight data [4–11]. One key to this progress was the development of computational fluid dynamics (CFD) solvers with adaptive mesh refinement (AMR) and immersed or embedded boundary methods to represent the complex deforming parachute surface and model its porosity. Another was the coupling of these CFD solvers to advanced finite element structural dynamics solvers with geometrically non-linear elements to model the large deformation of the parachute. We have yet to reach the point where FSI can reliably and accurately predict the parachute force as a function of time for supersonic disk-gap-band inflations. However, the relative errors are decreasing year-over-year and the qualitative behavior of the parachute is now reliably and accurately captured. FSI is mature enough to provide peak load deltas between cases where freestream conditions differ, and provide insight into the cause and effect of certain parameters.

So we propose a 2-stage approach to determine whether the Mars SRL deployment conditions would lead to loads exceeding those seen in SR03. First, we use a back-of-the-envelope approach to estimate peak parachute force that has been used and validated for past missions to Mars. Second, we perform fluid-structure interaction (FSI) simulations of the Mars 2020 entry vehicle and parachute system at Mars 2020 conditions and SRL conditions to compute deltas to apply to the recorded values. The FSI predictions are then used to extract and compare engineering strains across the two cases.

III. SRL Peak Parachute Force Estimation

A standard approach to estimate drag on blunt supersonic objects with minimal empiricism is:

$$F_{\text{chute}} \approx 2q_{\infty} K_p S_{\text{proj}}, \quad (1)$$

where K_p represents the available momentum flux going into the canopy that can be converted into drag, and S_{proj} is the projected area of the inflated canopy [12]. We compute the canopy projected area using the as-constructed band radius, yielding $S_{\text{proj}} \approx 196.14 \text{ m}^2$ for Mars 2020. The values of K_p computed from flight data from past missions to Mars and ASPIRE flight tests all fall within the narrow range of [0.75, 0.83]. Using the maximum K_p value of 0.83, we estimate peak F_{chute} for SRL at 882.9 Pa dynamic pressure:

$$F_{\text{chute}} \approx [259.76, 287.43] \text{ kN}. \quad (2)$$

By this metric, it appears that re-using the Mars 2020 parachute system for the SRL mission should be safe as the estimated maximum peak load would fall below that of ASPIRE SR03 by 12 kN. This corresponds to a rather thin margin of 4%. Moreover, the range of K_p was determined from measurements where parachute were deployed at $M \leq 2$, so it's possible that SRL could exceed this range at $M = 2.38$. More analysis is required to reduce mission risk.

IV. Simulation Methodology

The Launch, Ascent, and Vehicle Aerodynamics (LAVA) simulation framework is developed at NASA Ames Research Center [13]. It features three computational fluid dynamics (CFD) grid paradigms – structured overset curvilinear, structured Cartesian with adaptive mesh refinement (AMR), and unstructured arbitrary polyhedra – and many multi-physics capabilities. The NASA Entry System Modeling project has funded the development of a finite element based computational structural dynamics (CSD) solver that can be coupled with the Cartesian AMR CFD solver to enable the capability to perform FSI simulations of parachute inflation [14]. The methodology is described in Boustani et al. [14], and was recently updated to include viscous effects and more accurate turbulence-resolving numerical fluxes tuned for wall-modeled large-eddy simulation (WMLES) in Cadieux and Barad [15]. The CFD methods are summarized in Table 2, whereas the CSD methods are summarized in Table 3. Loose-coupling of the CFD and CSD solver is utilized whereby the CFD computes the aerodynamic tractions on each element and passes them to the CSD solver which computes the displacement of each node and shares the new location of the parachute nodes with the CFD solver. To solve the problem of parachute self-contact during inflation, tractions on each element are augmented by contact forces computed by the contact mechanics module. Porosity of the canopy is modeled through the immersed boundary method in the CFD solver by using an analytical solution to the Darcy-Forchheimer equations [14]. The parachute material properties are described in Table 4. Previous studies validated the overall methodology by reproducing from first principles the ASPIRE SR01 and SR03 flights while exploring sensitivity to various modeling input parameters [14–18]. LAVA FSI simulations so far have over-predicted the ASPIRE flight tests by 10 to 20%. The ASPIRE flights featured a slender payload compared to the blunt aeroshells used in Mars missions. This significantly reduced the wake momentum deficit ingested by the parachute. So we perform FSI simulations of the Mars 2020 parachute inflation to further validate the methodology and to ground SRL predictions.

Table 2 CFD parameters for FSI simulations.

Parameter	Value	Note/Units
Discretization type	Conservative finite difference	In Shu-Osher form
Convective flux	Hybrid Weighted Compact Non-linear Scheme (4 th order)	See Cadieux and Barad [15] for details
Flux function	Rusanov	With WENO limiter [19]
Shock sensor	Ducros squared	Ducros et al. [20]
Viscous flux	Conservative 2 nd order centered	
Subgrid scale model	Vreman [21]	Constant coefficient
Wall function	Blended log law profile	Matches Musker's [22]
Time integrator	Strong Stability-Preserving Runge-Kutta (SSPRK)	Explicit 3-stage 3 rd order
CFL number	0.95	
Minimum mesh size	0.01	m
Refinement levels	12	2:1 ratio between levels
Mesh type	Cartesian AMR	using small scale energy error metric [23]
Mesh size	200 to 1300×10 ⁶	Cells
Domain size	$L_x = L_y = L_z = 903.344$	m
Aeroshell motion	None	Mimics infinite mass ratio inflation

The first step toward that goal is to use the gravity folding technique to let the parachute relax into a low projected area state [15]. Figure 1 shows snapshots of the gravity folding process: we perform a CSD simulation with contact,

Table 3 CSD parameters for FSI simulations.

Parameter	Value	Note/Units
Discretization type	Finite element method	Geometrically non-linear
Fabric elements	MITC3 triangular shells	With additional drilling DOF
Cable elements	Non-linear cables	No resistance to compression
Mass matrix	Lumped	
Time integrator	Explicit 2 nd order centered	With high-frequency damping
Critical time step ratio	0.3 - 0.4	
Minimum edge length	0.0254	m
Maximum edge length	0.051	m
Mesh size	$\approx 300 \times 10^3$	Elements

Table 4 Finite element type and material properties [10, 11] for each component of the structural model.

Component name	Element type	Young's modulus (Pa)	Poisson ratio	Density (kg/m ³)	Radius (m)	Thickness (m)
Bridles	Non-linear cable	1.6680×10^{10}	0.4	705.13	0.0195	-
Riser	Non-linear cable	1.8600×10^{10}	0.4	751.99	0.0239	-
Suspension, gap, vent lines, gore seams	Non-linear cable	1.8202×10^{10}	0.4	484.66	0.0025	-
Broadcloth	MITC3	6.75×10^8	0.515	848.00	-	7.620×10^{-5}
Band leading edge	MITC3	1.3568×10^{10}	0.4	454.07	0.0029	-
Band trailing edge	MITC3	1.3568×10^{10}	0.4	454.07	0.0029	-
Disk leading edge	MITC3	1.3568×10^{10}	0.4	454.07	0.0029	-
Disk trailing edge	MITC3	1.0979×10^{10}	0.4	525.54	0.0045	-

holding parachute bridles fixed while gravity forces the canopy to fold. To reduce oscillations and reach steady state, we apply strong velocity-squared damping to all cable elements. We increase vent line density a hundred-fold to ensure tighter folding and smaller projected area. By the end of the simulation the parachute has folded to the area of the vent hole, corresponding to 10% of the as-constructed parachute diameter. This precursor simulation provides an initial parachute state representative of line stretch configurations: asymmetric, in self-contact, and relatively unstrained. The mean engineering strain over the disk and band are 9×10^{-6} and 3×10^{-6} respectively, whereas the maximum of their 99% confidence interval ($\bar{x} + 2.576 \sigma$) are 7×10^{-4} and 3×10^{-4} .

Table 5 Freestream conditions corresponding to inflation peak and gas properties used for FSI.

	q (Pa)	M	V (m/s)	α (°)	β (°)	γ	R (J/(kg K))
Mars 2020	504.1	1.76	404.8	-0.4	1.92	1.333	190.8
Mars SRL	882.9	2.38	518.8	-0.4	1.92	1.332	190.9

Table 6 Gas transport properties for used for Sutherland's Law in FSI.

Pr	μ_0 ($\times 10^{-5}$ Pa s)	T_0 (K)	S (K)
0.7592	2.018	292.25	127.0

We perform a CFD simulation of the rigid Mars 2020 aeroshell for 300 convective time units (CTU) at each freestream condition to allow aerodynamic loads to reach statistically stationary values and the aeroshell wake to extend

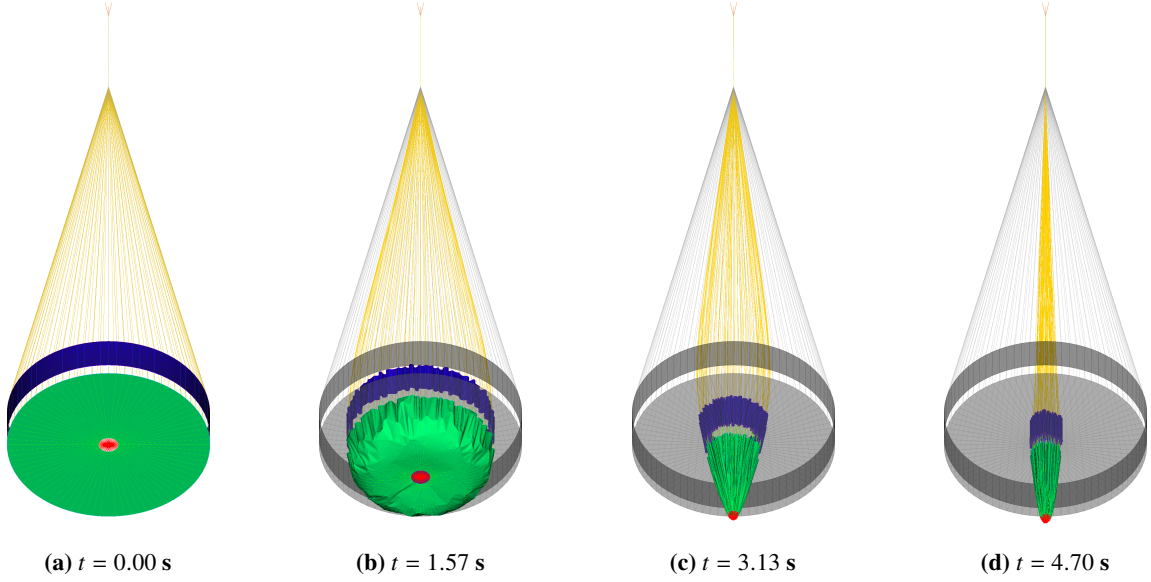
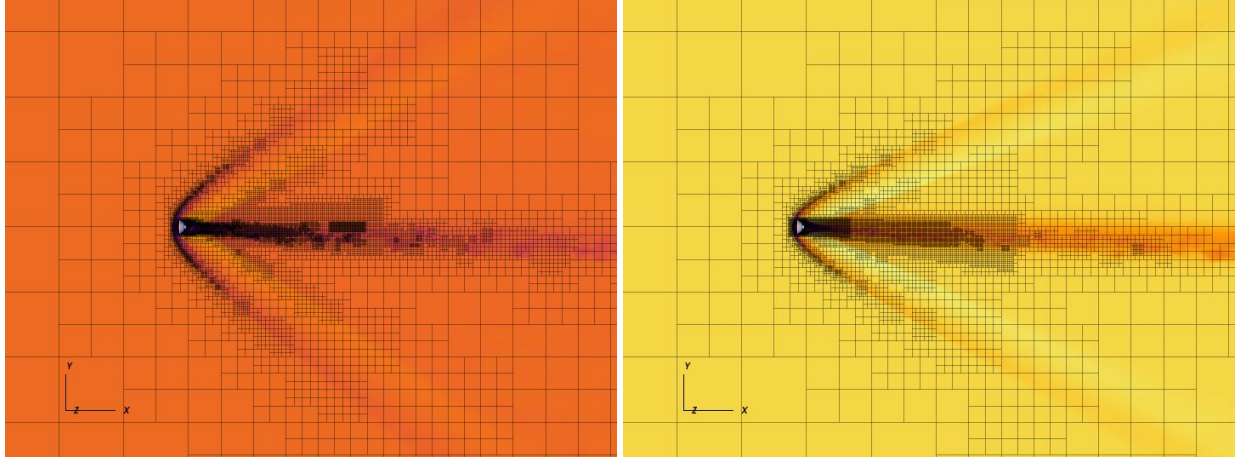


Fig. 1 Snapshots from the CSD simulation with contact mechanics of the parachute system folding itself under gravity. The as-constructed parachute system is shown with transparency in light gray, whereas the parachute system is shown colored by its various components as it folds.

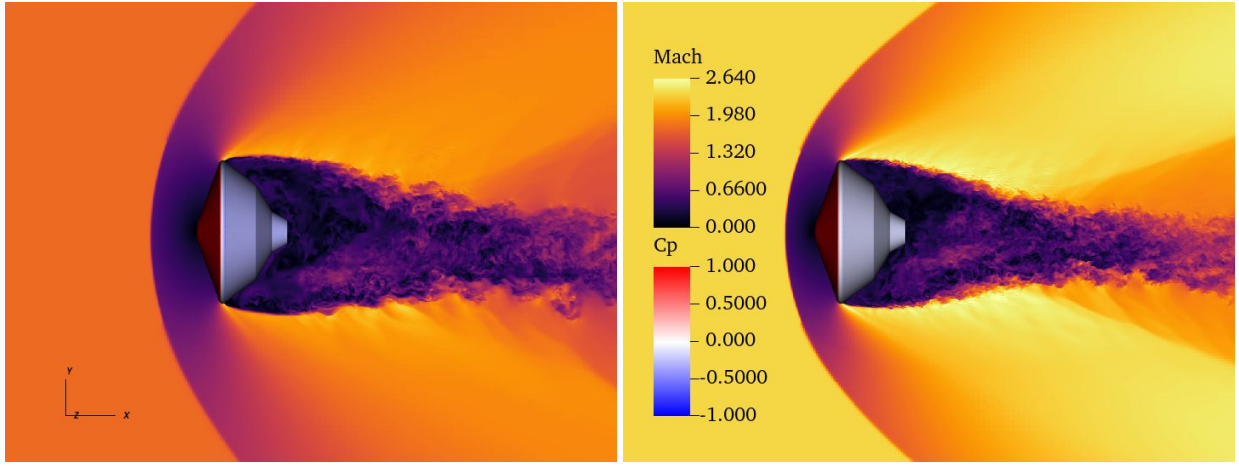
beyond the parachute plane. Figure 2 shows the CFD mesh on a slice, with black squares representing tile outlines containing 8^3 cells each. Two zoom levels display the refinement zones and flow solution at a snapshot before FSI begins. Figure 3 includes the drag coefficient history of the entry vehicle, and a time-averaged value using the last 100 convective time units ($CTU = t \times (V/L)$ where L is the diameter of the aeroshell). The Mach number slice shows that the fully-developed aeroshell wake extends past the parachute plane at line stretch. The drag time history confirms that a statistically stationary state has been reached in the aerodynamic loads. As expected, the SRL case produces a slightly larger drag coefficient due to the higher Mach bringing the bow shock closer to the heat shield and increasing the pressure difference between the front and the back of the aeroshell. Lift and side force coefficients remain in good agreement across the two cases. Moment coefficients show slightly more noticeable deviations, but are also consistent across the two cases. This is likely due to the turbulent and potentially asymmetric fluctuations in the separated shear layer near the shoulder of the heat shield where the moment arm is largest.

V. Results

FSI simulations start from the above-mentioned aeroshell-only CFD simulations and add the gravity-folded parachute. Figure 4 shows the time evolution of the Mars 2020 FSI simulation through snapshots at various times corresponding to important events. One salient distinction between these simulations and previous ASPIRE FSI simulations is the presence of the blunt aeroshell producing a large turbulent wake. The wake momentum deficit is partially ingested by the chute during inflation, as can be seen in the upper panels of Figure 4. In the subsequent panel, the entirety of the wake is ingested and interacting with the bow shock forming ahead of the partially inflated canopy. Predicted parachute shapes remain consistent across Mars 2020 and SRL simulations, despite differing freestream conditions. This is expected because the instants in time are different and chosen based on the parachute drag versus time curve. The most noticeable differences are caused by the change in freestream Mach number. Increased Mach number reduces the bow shock standoff distance and steepens the bow shock and recompression (fish-tail) shock angles relative to the vehicle axis. Similar effects can be seen near the parachute, with the addition of a stronger barrel shock at the exit of the vent hole and more powerful supersonic jets coming out of the gap between band and disk. Figure 5 shows the parachute after it has reached peak inflation and pushed the bow shock further upstream, reducing canopy pressurization. The parachute has a lower projected area and many of the lines experience reduced tension as a result. This transient event subsides quickly; the canopy re-pressurizes and moves out of the aeroshell wake plane, which increases canopy pressurization again and brings the lines under large tension. The parachute system then experiences the “rebound” peak.



(a) Overview of CFD mesh and solution



(b) Close-up of flow over aeroshell

Fig. 2 Slice through the CFD mesh for the rigid aeroshell simulation showing Mach number on the slice, pressure coefficient (C_p) on the surface, and the outlines of 8^3 cell tiles in black lines on the slice near the end of the 300 convective time unit simulation. Left column corresponds to the Mars 2020 freestream conditions whereas right column corresponds to SRL. Legend shown on the bottom right panel applies to all panels.

The aeroshell moves at constant freestream velocity, approximating an infinite mass ratio inflation. This approach captures peak loads accurately because the aeroshell decelerates minimally between line stretch and peak inflation [3]. Figure 6 shows the FSI predicted parachute force as a function of time from line stretch along with the Mars 2020 parachute force reconstructed from filtered accelerometer measurements on board the entry vehicle. We shift FSI results in time to align peaks with Mars 2020 measurements (see Table 7). Consistent with previous SR03 simulations, FSI underpredicts inflation time by nearly 25%. This is likely due to how the FSI is started as well as the initial shape of the parachute and its projected area, but remains an active area of research. FSI also overpredicts peak inflation force by 16%, consistent with previous SR03 simulations [15] due to unchanged parachute model and methodology. Future work will investigate this overprediction in detail. Despite this overprediction, peak width and post-inflation trough values compare well with Mars 2020 measurements. The slope of the rebound peak immediately after the trough is also well-predicted, even though FSI predicts a larger parachute force beyond the trough. This difference is expected because the Mars 2020 vehicle decelerates rapidly due to parachute drag, whereas our simulation maintains constant freestream conditions. The restrained aeroshell approach loses fidelity beyond 0.8 s after line stretch due to vehicle deceleration. Restrained aeroshell simulations conservatively estimate post-inflation behavior, as parachute drag should approach a statistically stationary value.

We compare flight-reconstructed projected area from up-look stereo cameras with FSI predictions in Figure 7.

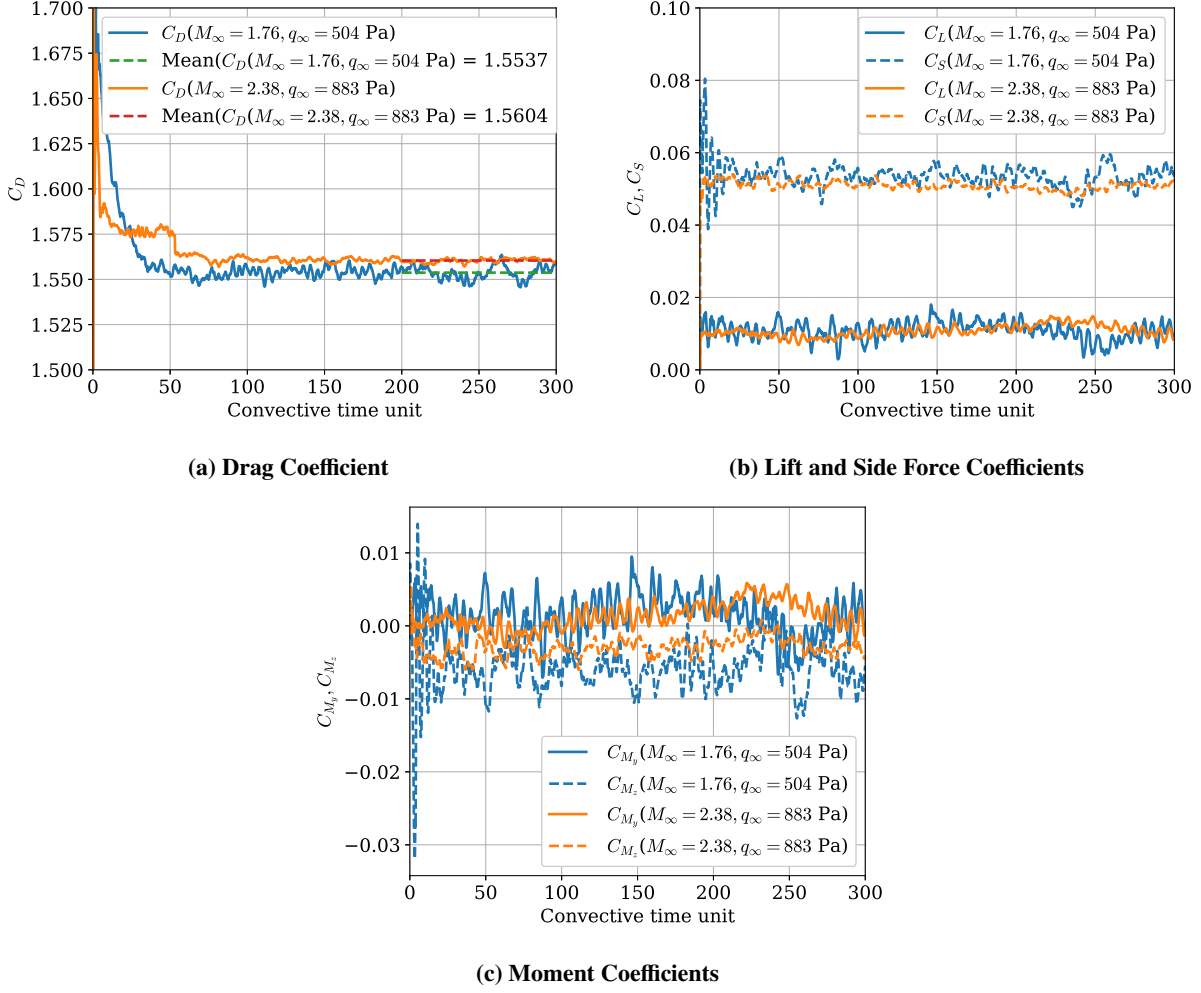


Fig. 3 Aerodynamic coefficients as a function of convective time unit for the entry vehicle at the Mars 2020 and SRL freestream conditions. Roll moment in the body frame (C_{M_x}) is not plotted for brevity because it is nearly zero.

Camera calibration issues make absolute Mars 2020 projected area values unreliable. The reconstructed maximum projected area of 220 m^2 is highly suspect in that significantly exceeds the reference area ($S_{\text{ref}} = 196.14 \text{ m}^2$). Moreover, the ASPIRE SR02 and SR03 flight tests, which featured a nearly identical parachute system but had properly calibrated cameras, demonstrated projected areas at their inflation peak of 188 m^2 and 172 m^2 , respectively [24]. Their respective rebound peaks reached slightly larger projected areas of 193 m^2 and 181 m^2 [24]. And their maximum projected area over the first 2 seconds after line stretch never reached beyond 196 m^2 [24]. In light of this, we use non-dimensional projected area ($S_{\text{proj}}(t)/\max(S_{\text{proj}})$) for qualitative comparison. We shift FSI projected area curves using the same time offset applied to parachute force. Although FSI predicts consistent inflation slopes and post-inflation behavior with Mars 2020, peak projected area occurs earlier in time. The fact that the peak loads occur before the parachute reaches its maximum projected area is well documented across all ASPIRE flights [2]. FSI simulations underpredict this lag. Combined with drag overprediction, this suggests FSI underpredicts canopy porosity at high strain. This is consistent with results from As'ad et al. [11] where porosity was scaled with canopy element area ratio leading to a decrease in peak parachute drag.

The FSI clearly reproduces the overall qualitative behavior of the Mars 2020 parachute system and provides a conservative prediction of the inflation peak load, as well as the post-inflation trough and rebound peak as shown in Table 7. The FSI at higher Mach and dynamic pressure is then utilized to predict SRL loads. The FSI predicted peak parachute force for SRL of 281 kN falls right within the empirically predicted range derived in (1). The equivalent K_p

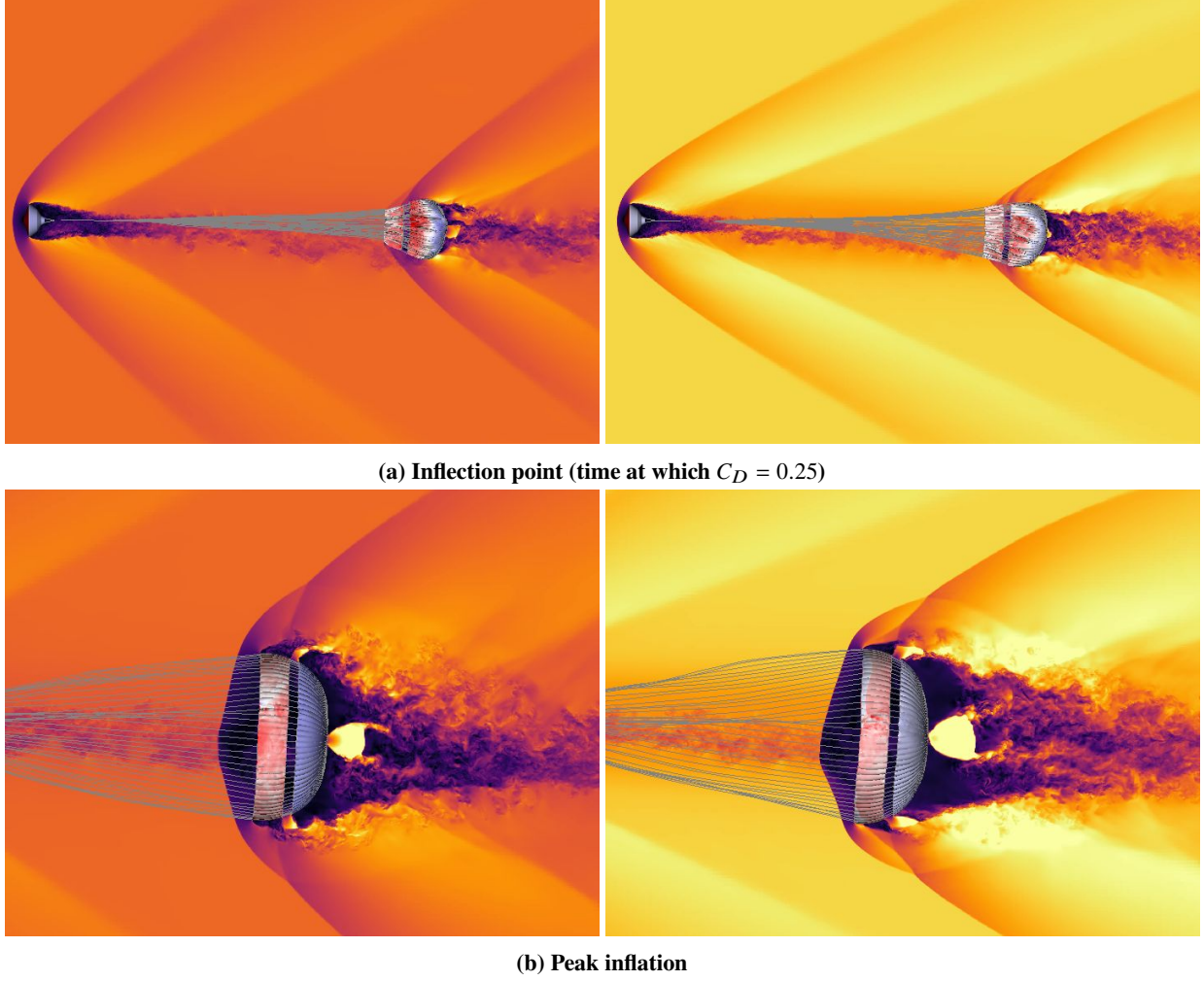


Fig. 4 Slice of the FSI simulations showing Mach number, pressure coefficient (C_p) on the surfaces, and the parachute line elements in gray at important events during inflation. Left is at Mars 2020 freestream conditions and right is at SRL conditions. Legend is identical to Fig. 2.

Table 7 Comparison of quantities of interest across flight and FSI.

	Mars 2020	$M = 1.76, q = 504 \text{ Pa}$	$M = 2.38, q = 883 \text{ Pa}$
Time offset to align peak (s)	0.000	0.165	0.154
Time to inflation peak F_{chute} (s)	0.64	0.48	0.49
Inflation peak F_{chute} (kN)	152	177	281
Post-inflation F_{chute} trough (kN)	75	56	70
Post-inflation rebound F_{chute} peak (kN)	144	175	284
First peak in S_{proj} (m^2)	220	194	195
Time to first S_{proj} peak (s)	0.71	0.67	0.65
Time lag from F_{chute} peak to S_{proj} peak (s)	0.07	0.03	0.01

value for SRL is then 0.81 which fits neatly within the expected range of 0.8 ± 0.1 used for Mars 2020 predictions [3]. The peak inflation load increment from comparing the two FSI is 104 kN. If we apply this increment to the Mars 2020 flight data, we obtain a slightly lower inflation peak estimate of 256 kN. This results in a slightly lower K_p value of 0.74,

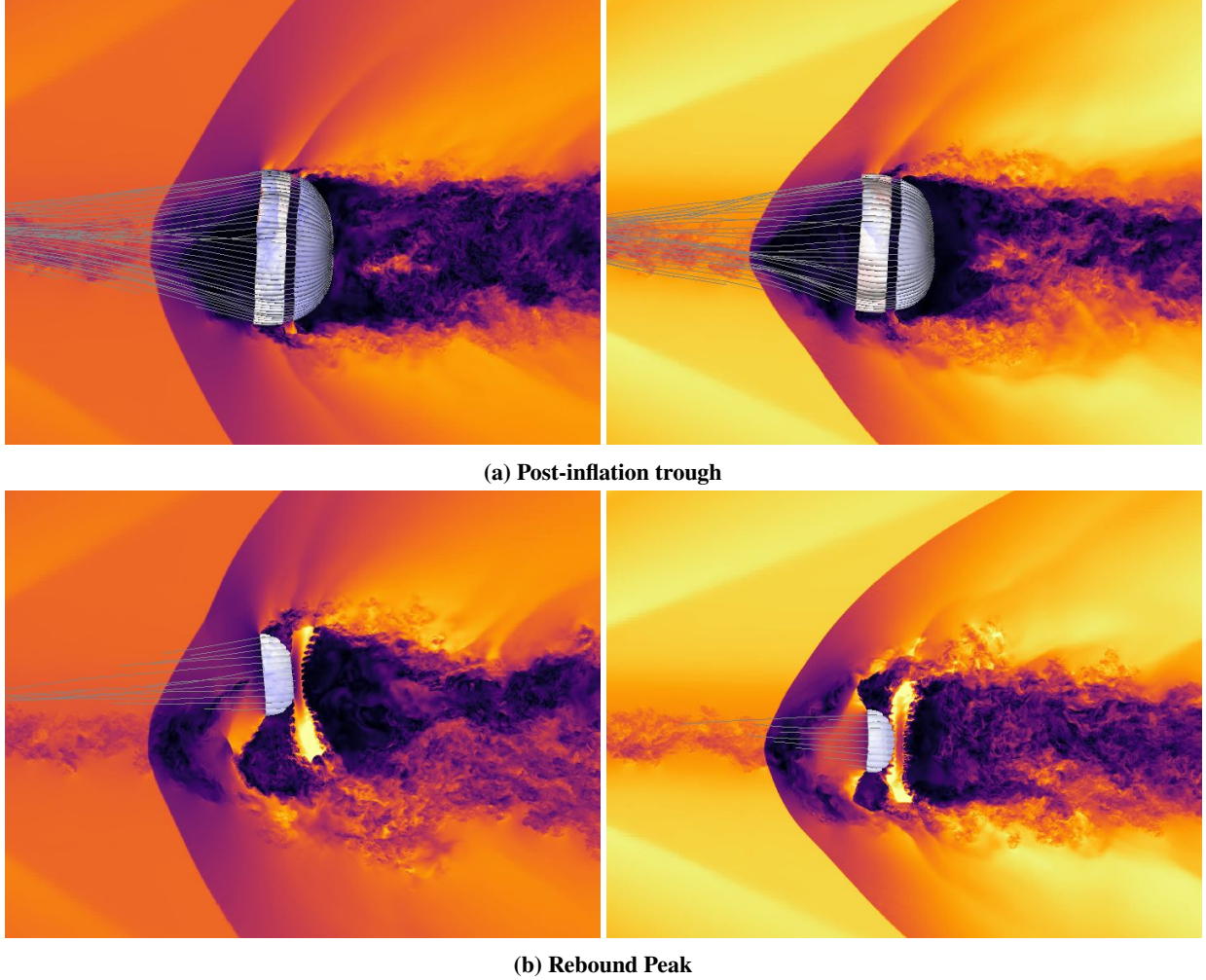


Fig. 5 Slice of the Mars 2020 FSI simulation showing Mach number, pressure coefficient (C_p) on the surfaces, and the parachute line elements in gray at important events post-inflation. Left is at Mars 2020 freestream conditions and right at SRL conditions. Legend is identical to Fig. 2.

dipping just below the lower bound of recent supersonic parachute flights but still well within the Mars 2020 assumed range [3].

Figure 6 also shows the drag coefficient history for the Mars 2020 mission along with the FSI predictions for Mars 2020 and SRL with respect to convective time units. This transformation collapses the two FSI curves over much of their range. The notable exception is that the inflation time (in seconds) between the two cases is nearly identical. This is because the higher freestream Mach number causes a stronger bow shock and reduces the post-shock velocity and dynamic pressure acting on the canopy. Additionally, the entry vehicle experiences higher drag at SRL conditions and causes a larger momentum deficit in its wake, which reduces the available momentum for the parachute to inflate. The projected areas of the two FSI are almost on top of each other after 0.4 s and reach nearly the same peak projected area as shown in Figure 7. This reinforces that the lower drag coefficient must be due to increased aeroshell wake momentum deficit ingested by the parachute.

Although peak load predictions support reusing the Mars 2020 parachute for SRL, other factors merit consideration. Higher Mach numbers increase parachute area oscillations, as evidenced by FSI predictions of deeper post-inflation troughs and larger rebound peaks. Localized strains during inflation may exceed material strength [25]. Because direct strain measurement under representative conditions is not yet possible, we use FSI comparisons to inform the design decision. FSI provides complete spatiotemporal strain and stress distributions over all finite elements. Extracting meaningful insights from this spatiotemporal data is challenging. FSI stress predictions lack experimental validation

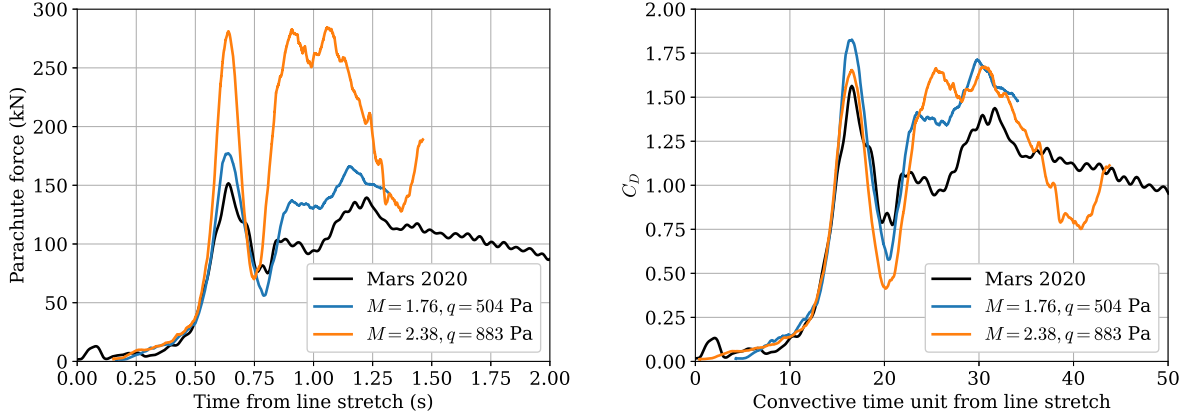


Fig. 6 Parachute force (left) and drag coefficient (right) comparison between LAVA FSI and Mars 2020 flight data from filtered accelerometer measurements [3].

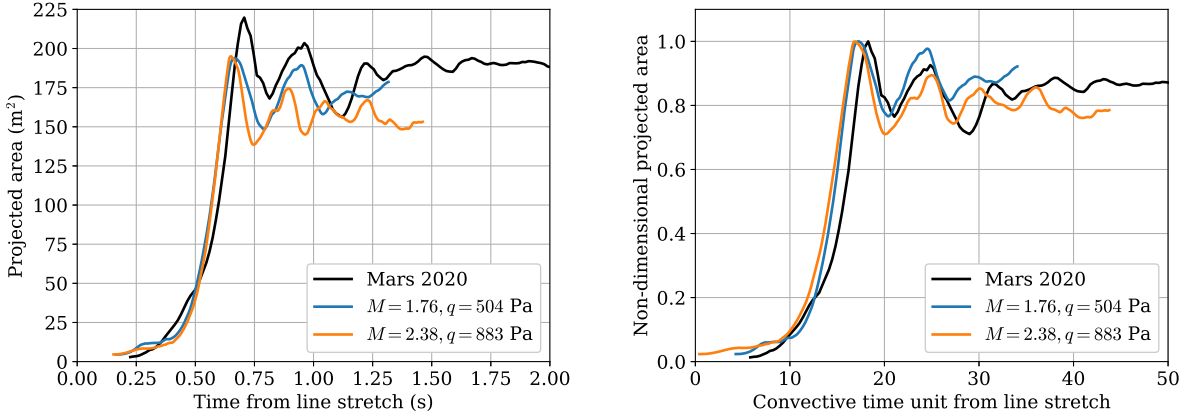


Fig. 7 Parachute projected area (left) and non-dimensional projected area (right) comparison between LAVA FSI and Mars 2020 flight data reconstructed from high-speed up-look cameras [3].

for fabrics and braided chords at large strains and high strain rates. The parachute community distrusts FSI-predicted stresses due to simplified material models (Saint-Venant Kirchhoff, isotropic) and neglected fore-shortening in vent lines and gore seams. These details significantly alter local radii of curvature and stresses. Thus, we analyze engineering strain (ϵ), which is more interpretable and easier to validate in the future. For triangular disk and band elements, we compute engineering strain as $\epsilon \approx \sqrt{A/A_0} - 1$, a standard large-strain approximation for membranes where A is deformed area and A_0 is initial area. For line elements, the engineering strain is computed as $\epsilon = (L - L_0)/L_0$ where L is the length of the deformed element and L_0 is its initial length. To reduce the dimensionality and exclude outliers, we examine the average and maximum of the 99% confidence interval (CI) of ϵ strain values across parachute components. Figure 8 shows the average and maximum of the 99% CI(ϵ) over the components of the disk and band that are the most likely candidates for failure as a function of time. Engineering strain curves correlate well with parachute force curves (Figure 6), with peaks occurring nearly simultaneously. During the first 0.6 s, maximum 99% CI strain significantly exceeds the average. Large strains concentrate in few elements as the disk unfolds due to extensive self-contact, restricting its motion. This difference is less pronounced in the band initially but grows rapidly. Both simulations show consistent behavior until 0.5 s across all components. After $t = 0.5 \text{ s}$ the SRL average strains exceed those of the Mars 2020 simulation, except during the post-inflation trough. The SRL maximum 99% CI(ϵ) follows a similar pattern when compared with its Mars 2020 counterpart. The maximum 99% CI strain ratio between SRL and Mars 2020 is larger in the disk, as expected for the primary drag surface. Maximum 99% CI strain across all components

remains below 3%, briefly reaching 2.5% only during inflation and rebound peaks. Maximum strain ratios between SRL and Mars 2020 occasionally exceed the dynamic pressure ratio (1.75) but rarely exceed the Mars 2020–SR03 ratio (2.04). The disk inflation and rebound peaks exceed the 2.04 ratio, warranting closer examination. Rebound peak concerns are mitigated somewhat because the restrained aeroshell approach conservatively estimates post-inflation behavior. To retire the concern about the rebound peak, we plan to perform FSI simulations with free flight (6 degrees of freedom) aeroshells to obtain more representative strains in the post-inflation phase. We plan to analyze the engineering strain from our previous ASPIRE SR03 FSI simulations to determine whether the maximum strains predicted for SRL exceed those of SR03, and by how much.

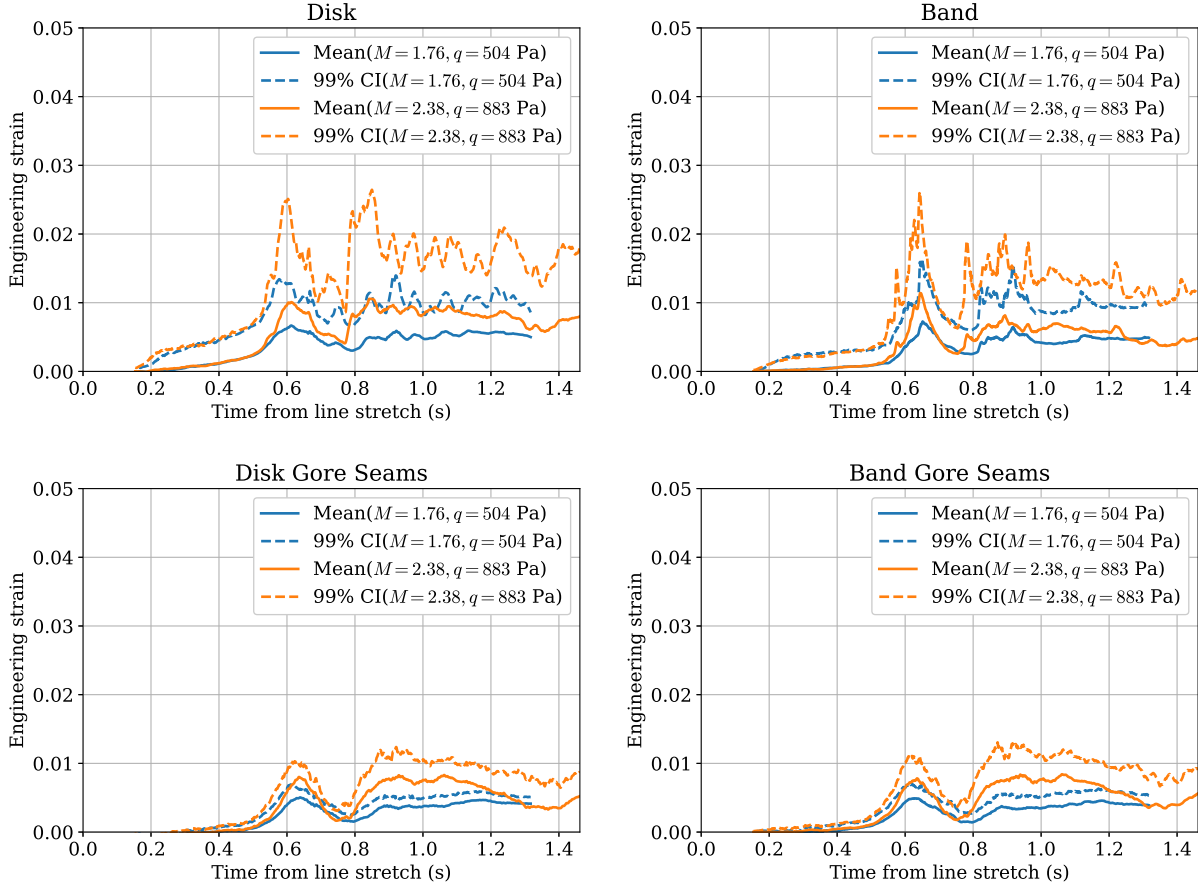


Fig. 8 Average and maximum engineering strain over disk and band components as a function of time.

The average and maximum 99% CI(ϵ) in the various line elements of the parachute system as a function of time are shown in Figure 9. Suspension, gap, and vent line behavior matches that of the gore seams they are attached to. Suspension and gap line curves are almost identical to their corresponding band gore seams curves. Lines experience lower strain than canopy fabric due to stiffer materials. The spread between average and maximum strain is smaller in lines than in fabric. This indicates more uniform strain distribution rather than localized concentrations. The 99% CI(ϵ) also shows fewer peaks in the lines compared to the disk or band (less intermittency). Bridles show higher strain intermittency after rebound and when the parachute strays from the aeroshell wake axis. Asymmetric loading increases bridles' 99% CI(ϵ) and also explains the higher intermittency. This effect likely stems from the restrained aeroshell approach and should diminish in free flight simulations.

VI. Conclusions

The Mars SRL mission plans to reuse Mars 2020 mission architecture and hardware to minimize risk and cost. To assess Mars 2020 parachute safety for SRL, we estimated peak loads empirically and compared them to ASPIRE SR03

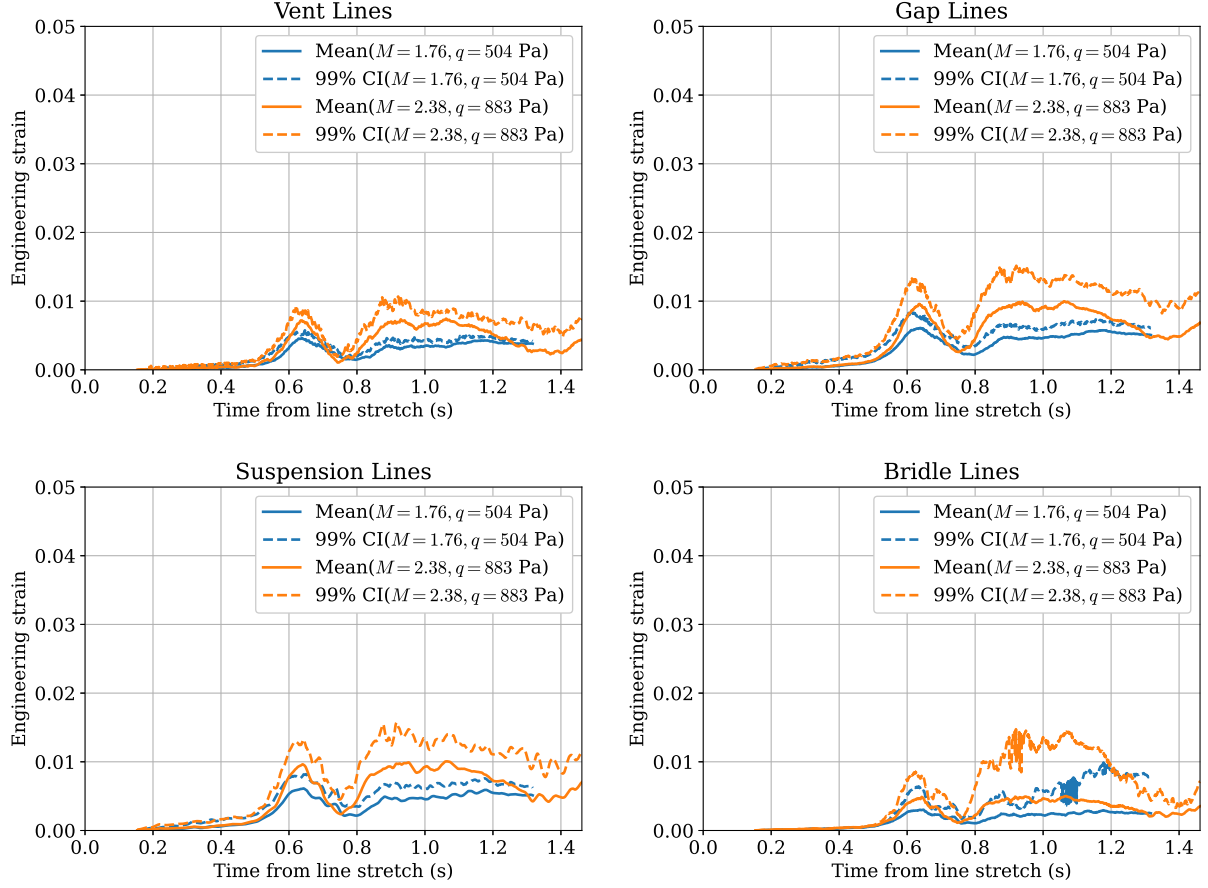


Fig. 9 Average and maximum engineering strain over line components as a function of time.

measurements. The empirically estimated peak load is 4% below SR03 measurements, suggesting a small margin. Infinite-mass ratio inflation FSI predictions agree reasonably with reconstructed parachute force and projected area from the Mars 2020 mission, though they underestimate inflation time and overestimate peak parachute force by 16%. The restrained aeroshell FSI simulation otherwise provides a conservative estimate of the Mars 2020 parachute force as a function of time. The SRL simulation predicts a peak inflation load within the expected range from previous flights using the momentum-based empirical estimate and falls below the ASPIRE SR03 peak load by 6%. Since previous FSI provided conservative estimates (larger than flight measurements), we derived a load delta from FSI values for Mars 2020 and SRL and applied it to Mars 2020 flight data, yielding a slightly larger margin of 14%. Although peak load analysis supports Mars 2020 parachute reuse for SRL, strain analysis supports a more nuanced conclusion. FSI-predicted disk maximum 99% confidence interval strains occasionally exceed the expected dynamic pressure ratio between Mars 2020 and SRL (1.75) and even reach the Mars 2020 to SR03 ratio (2.04). More analysis is required to determine whether the strain experienced by SRL could exceed ASPIRE SR03 levels.

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