

Fluid-Thermal-Structural Interactions in Ramp-Induced Shock-Wave Boundary-Layer Interactions at Mach 6

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I. Introduction

Shock-wave boundary-layer interactions (SWBLI) pose unique challenges for the slender airframes and sharp control surfaces characteristic of high-speed airbreathing aircraft. Spikes in pressure and thermal loading have been shown to occur in SWBLI regions; thus, predicting their location and behavior proves critical for assuring aircraft structural integrity and fatigue resilience.¹ SWBLIs frequently lead to severe turbulent boundary-layer separation and corresponding unsteady motions characterized by a wide range of frequencies.² Low-frequency motion has been shown to couple with the structure of a compliant panel, and turbulent boundary layers thus present a particular danger for thin control surfaces.³

Previous studies have shown that the thermal loading on a compliant panel in a ramp-induced SWBLI may have a significant impact on the panel vibrations.⁴ A multitude of studies has investigated the heating on rigid structures,⁵ but a characterization of the heating effects on compliant structures is necessary to fully understand the fluid-thermal-structural interactions (FTSI) occurring in ramp-induced SWBLIs. This study uses infrared thermography and high-frequency Kulite pressure transducers to examine the heating loads on rigid and compliant ramps at various angles and flow conditions at Mach 6.

II. Experiments

A. Facility

The tests were conducted in the NASA Langley Aerothermodynamics Laboratory 20-Inch Mach 6 blow-down wind tunnel.⁶ The facility uses dried, heated, and filtered air and is capable of 20 minute run times, although these experiments lasted approximately 10 seconds each to allow for multiple runs per day. The test section measures 520.7 mm by 508 mm and has 6 windows for optical access. For these experiments, the top, front optical access point is fitted with a special Zinc Selenide (ZnSe) antireflective-coated window to allow for infrared (IR) thermography testing. The nominal reservoir conditions are stagnation pressures of 0.21-3.3 MPa with stagnation temperatures of 422-556 K, producing flows corresponding to unit Reynolds numbers of

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$1.6\text{--}24 \times 10^6 \text{ m}^{-1}$.⁷ This study operated at two unit Reynolds number conditions to examine the interactions of both transitional and turbulent boundary-layers with ramp-induced shocks: $6.6 \times 10^6 \text{ m}^{-1}$ and $23.6 \times 10^6 \text{ m}^{-1}$ were chosen based on a transition study of this model and facility by Kegerise et al.⁷

B. Model

The base of the model consisted of a 280 x 711 mm steel flat plate with a sharp leading edge and a 102 mm-wide channel along the centerline for inserts. Two 15-5 PH/H1025 (AMS 5659) stainless steel ramps were placed 356 mm downstream of the leading edge to generate a compression corner. The 'rigid' ramp measures 203 mm wide by 102 mm long and is 7.62 mm thick. The side edges are machined to a sharp point such that when the ramp assembly is inserted into the flat plate, the leading edge of the ramp is flush with the surface of the flat plate. KaptonTM tape was used to prevent throughflow beneath the ramp side extensions. The 'compliant' ramp has the same general geometry as the rigid ramp with a 76.2 x 88.9 mm rectangular cavity machined out of the back. This results in a 0.5 mm thick clamped panel embedded in the surface of the ramp. The upstream edge of this plate is co-located with the corner of the compression ramp. The ramps are placed on interchangeable angled brackets to produce ramp angles of 10°, 20°, 30°, and 35° to span flow conditions from attached to fully separated.

To prevent a static pressure deformation of the compliant panel, a plenum box was designed to create a pressure controlled environment on the lee-side of the panel. The cavity generated by the plenum box and ramp measures 15.7 x 76.2 x 88.9 mm and is controlled by a 15 psia pressure calibration unit. The back pressure was set to match the static post-shock pressure on the flow side calculated using inviscid theory.

Boundary layer trips were placed 87.4 mm downstream of the leading edge in order to produce a fully turbulent flow over half of the desired interrogation area of the ramp. The trips have a square shape with a side length of 2.16 mm, and are oriented such that the faces of each roughness element are oriented at 45° to the incoming flow. The trips protrude 3.05 mm into the flow and are pitched 6.6 mm apart. The placement of the trips was chosen based on the expected lateral spreading angle of approximately 3°.⁸

The flat plate was instrumented with a flush-mounted fast-response, piezoresistive KuliteTM pressure transducer (XCS-062), placed 38.2 mm upstream of the compression corner along the centerline of the model. Both ramps were instrumented with three flush-mounted XCE-062 sensors located 96.5 mm downstream of the corner along the ramp, -19, 0, and 19 mm from the centerline. The plenum box was instrumented with two XCE-062 sensors to measure the fluctuations in the pressure inside the cavity. The pressure measurements were collected by three Dewetron TRION-2402-dSTG universal input modules at 200 kHz. To verify the measurements from the infrared camera, two type-J beaded thermocouples were mounted flush with the surface of the rigid ramp, 3.81 mm on either side of the centerline, and 42.7 mm downstream of the compression corner. Three stick-on type-E thermocouples were placed on the lee-side of the compliant panel, 37.3 mm downstream of the compression corner and -19, 0, and 19 mm from the centerline. The measurements from the thermocouples were collected at 50 Hz.

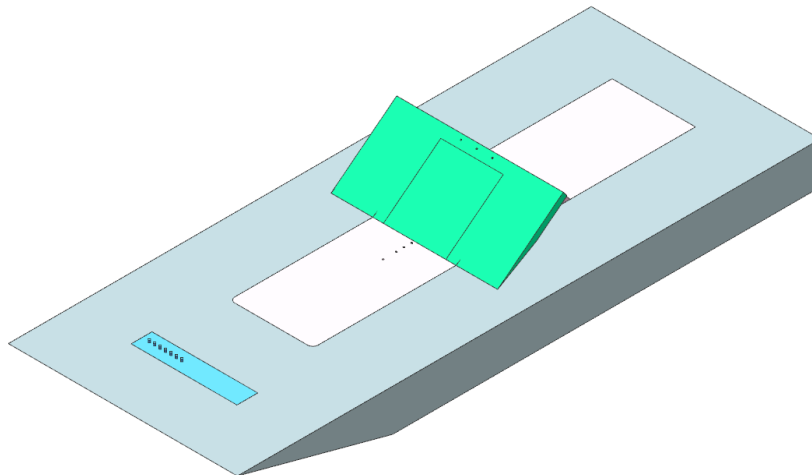


Figure 1: CAD rendering of the model with trips.

C. Pitot Rake

A pitot rake was used to measure the boundary layer along the centerline of the model at the compression corner location. The rake is made from stainless steel and consists of 12 stagnation probes placed approximately 1.35 mm apart for a total height of 16.2 mm. Each probe has an outer diameter of approximately 0.58 mm. The rake was tested for four Reynolds number conditions, two of which were tested with and without the boundary layer trips (Table 1). To allow for experimentation with the rake, the ramp is removed from the flat plate and a steel block, with an insert for the rake, is mounted flush with the flat plate.

Table 1: Pitot Rake Run Conditions

Condition	Trips	Re_∞ (10^6 1/m)	P_0 (MPa)	T_0 (K)
A	Off	13.1	1.72	505
B	Off	3.3	0.40	491
C	Off	23.6	3.28	519
D	Off	6.6	0.86	505
E	On	6.6	0.86	505
F	On	23.6	3.28	519

D. Infrared Thermography

IR thermography is used to measure the surface temperature of the ramps. The surface of the entire model is coated with a thin layer of Rust-Oleum™ High Heat black paint, resistant to up to 1200°F. Benchtop calibration of the camera with a 15-5 PH/H1025 coupon coated in the black paint resulted in an emissivity of $\epsilon = 0.92$. A FLIR A655sc camera is used to measure the radiation emitted by the panel. The camera has a resolution of 640 x 480 pixels with a frame rate of 50 Hz and an uncertainty of $\pm 2\%$.

III. Preliminary Results

A. Boundary Layer

Pitot rake measurements were taken at four separate Reynolds numbers to produce a baseline understanding of the boundary layer state at the compression corner location. During preparations for the experiment, the probe at $h = 14.85$ mm sheared off and a clog was identified in the probe at $h = 2.7$ mm, therefore the measurements from these probes are omitted from the data. Furthermore, the druck in the probe at $h = 9.45$ mm caused faulty measurements from this port for conditions A and B, thus these data points are omitted as well. Figure 2 shows the stagnation pressures measured by the pitot rake. It is apparent that the trips significantly increased the boundary-layer thickness for condition C from ~ 5 mm to ~ 9 mm. As can be seen in Figure 3b, the rake is completely inside the tripped boundary layer region. Note that the plate in front of the rake is made from aluminum and thus has a much higher thermal conductivity compared to the rest of the steel flat plate.

The thermal images indicate that the untripped flow at $Re = 6.6 \times 10^6 \text{ m}^{-1}$ is in fact laminar and the untripped flow at $Re = 23.6 \times 10^6 \text{ m}^{-1}$ is transitional instead of transitional and turbulent as was expected from previous flat plate transition studies.⁷ The authors believe that this is due to the increased leading edge bluntness caused by the application of the black paint, thus delaying transition on the flat plate.

B. Panel Vibrations

Previous studies of a compliant panel under forcing generated by a SWBLI on a compression corner showed that a static deformation was caused by the pressure difference accross the panel.⁴ To correct this, the plenum box on the lee-side of the panel was pressurized to the post-shock static pressure calculated using inviscid theory. However, simulations of the panel behavior when placed at 35° at condition C show that the panel is expected to buckle under a thermal load generated by a temperature difference of approximately $\Delta T = 26$ K. This effect is discussed in the next section.

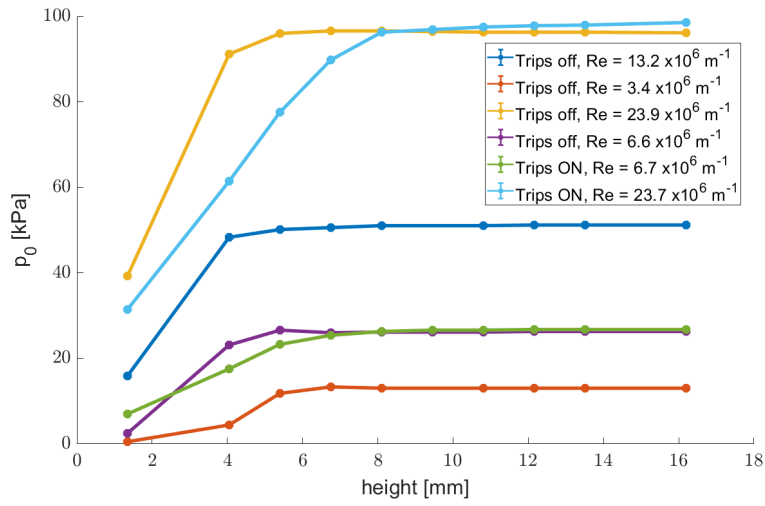


Figure 2: Pitot rake stagnation pressure distributions.

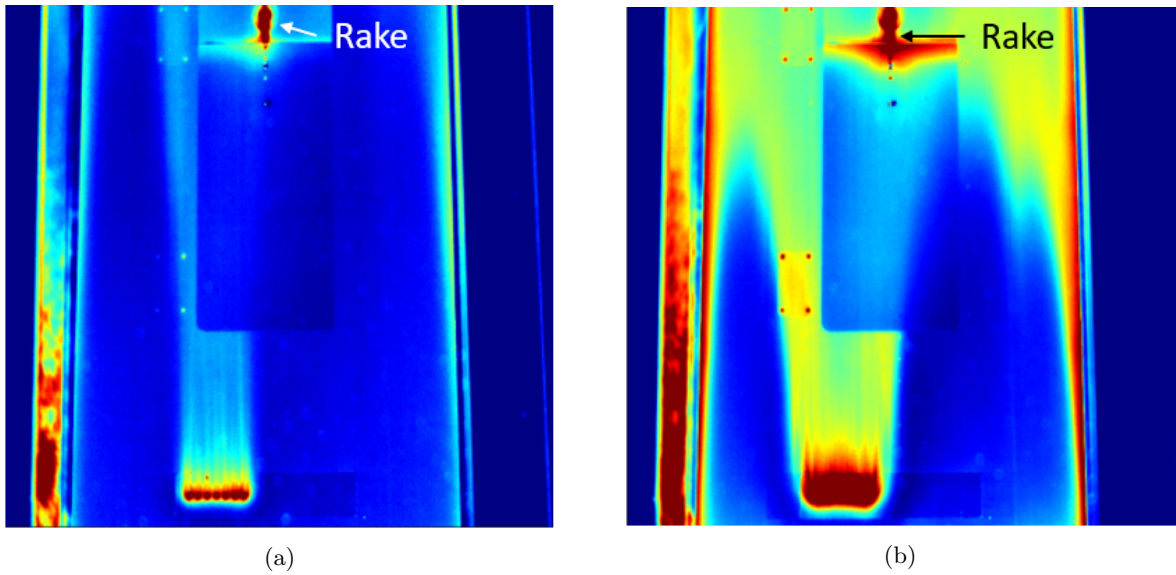


Figure 3: Thermal images of the tripped boundary layer on the flat plate at (a) $Re = 6.7 \times 10^6 \text{ m}^{-1}$ and (b) $Re = 23.7 \times 10^6 \text{ m}^{-1}$.

The theoretical panel vibrational natural frequencies are interpolated for a clamped plate with an aspect ratio $AR = 0.86$ from published data⁹ and are presented in Table 2. Since the panel vibrations produce variations in the static pressure inside the plenum box, the pressure transducers were used to study the vibrational frequencies of the panel during the experiments. Power spectral densities are calculated over 0.1 s time increments using Welch's method. Figure 5 shows the pressure spectra for the compliant ramp at 35° , without trips, and at the high Reynolds number condition. It is evident that the dominant low frequency modes are the spanwise symmetric (1,2) and (1,3) modes, at ≈ 1.19 kHz and ≈ 2.07 kHz respectively, which supports the assumption that, without the tripped boundary layer on half the panel, the flow is essentially two-dimensional. On the other hand, when the trips are introduced to the flow, the boundary layer now produces a different forcing on the left half of the panel compared to the right. This is evident in Figure 6 where the (2,1) mode is now present throughout the run at ≈ 1.42 kHz, indicating that the spanwise vibrations are asymmetric. A slight decrease in the frequencies of the lower two modes is visible while the higher mode appears to increase over time. More analysis is necessary to explain this behavior, although the author believes the two primary factors in the shift of frequencies are the panel buckling and temperature.

Table 2: Compliant Panel Natural Frequencies

m	n	λ (kHz)
1	1	0.65
1	2	1.19
2	1	1.42
2	2	1.94
1	3	2.07
3	1	2.66
2	3	2.77
3	2	3.13

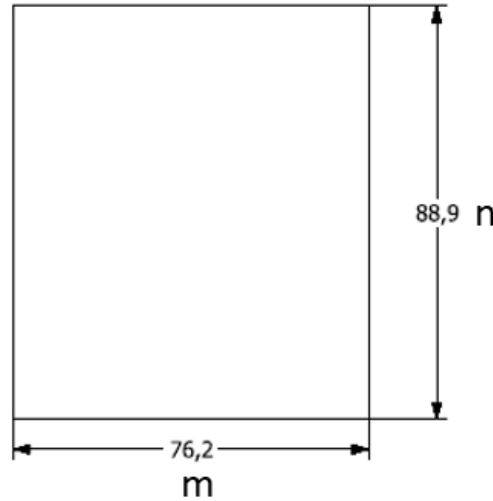


Figure 4: Panel geometry with respective mode labels.

C. Surface Temperature

The ramp surface temperature is obtained using IR thermography with a sampling frequency of 50 Hz. Figure 7 shows the surface temperature distribution for the compliant ramp at 35° at conditions C and F. An unexpected behavior occurs at this condition where there is a low temperature zone at about 33% of the panel length. This behavior is also evident in the case with the boundary-layer trips, however, rather

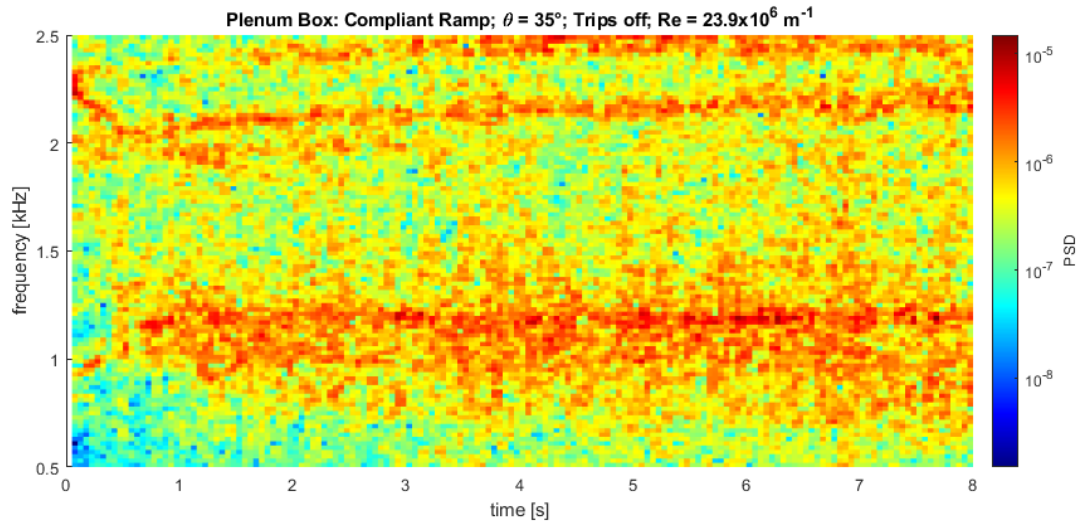


Figure 5: Time resolved PSD for the compliant ramp: $\theta = 35^\circ$, $Re = 23.9 \times 10^6 \text{ m}^{-1}$, trips off.

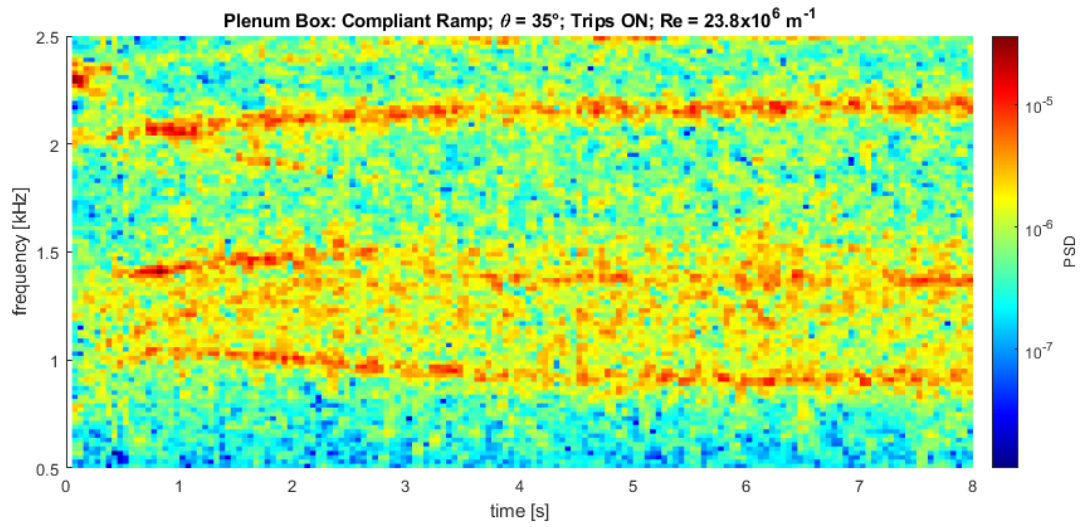


Figure 6: Time resolved PSD for the compliant ramp: $\theta = 35^\circ$, $Re = 23.8 \times 10^6 \text{ m}^{-1}$, trips on.

than being constant along the span of the panel, the low-temperature zone is shifted downstream on the side of the panel affected by the boundary-layer trips. This could be an effect of the panel buckling due to the temperature difference between the thin panel and the thicker ramp given that buckling is expected to occur for $\Delta T = 26$ K. Figure 8 shows that already at injection, the panel is close to the critical temperature difference for the onset of buckling.

At the lower Reynolds number, the surface temperature distribution on the compliant ramp follows the expected geometry. This is also true for all the rigid ramp cases where the temperature distribution is what consistent with the heat-flux distributions from other studies over similar geometries.¹⁰ The temperature increase for two of these cases is presented in Figure 9.

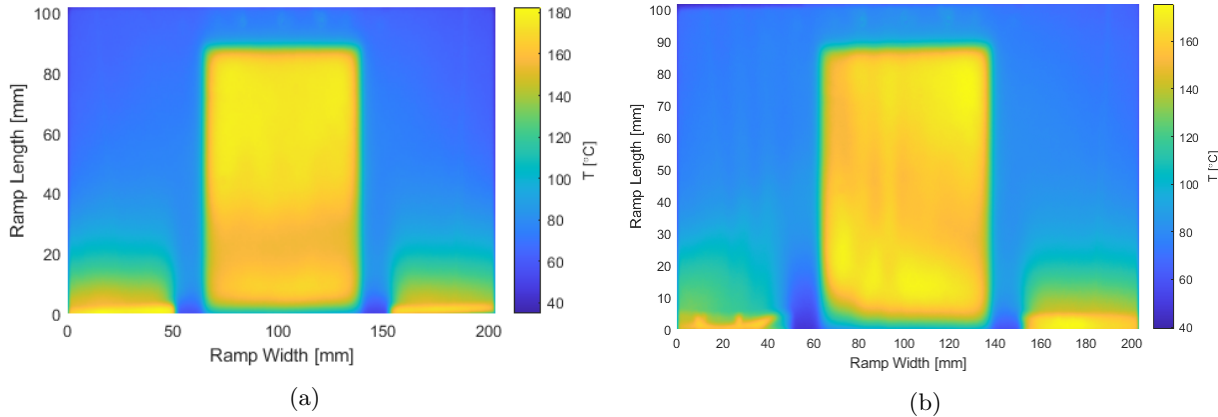


Figure 7: Thermal images of the compliant ramp at 35° and $Re = 23.7 \times 10^6 \text{ m}^{-1}$ (a) without boundary layer trips and (b) with trips 6 seconds after injection into the test section.

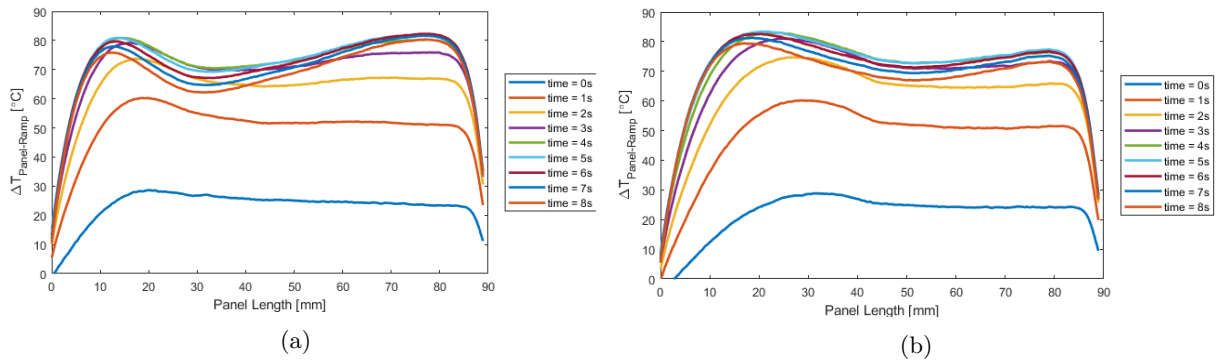


Figure 8: Half-span averaged temperature distributions of the compliant ramp at 35° and $Re = 23.7 \times 10^6 \text{ m}^{-1}$ on the side (a) without and (b) with boundary layer trips.

D. Heat Flux

An algorithm to generate heat flux distributions using the surface temperature data has not been completed yet, although we plan to use the Estorf or Liu methods for image based surface heat-flux calculation.^{11, 12}

IV. Conclusions

In this study, we conducted experiments on the fluid-thermal-structural interactions generated by compression corner shock-wave boundary-layer interactions at Mach 6 for a variety of ramp angles. Interesting behaviors have already been noted for certain configurations during this experiment and the determination of the heat flux will provide more information to analyze them.

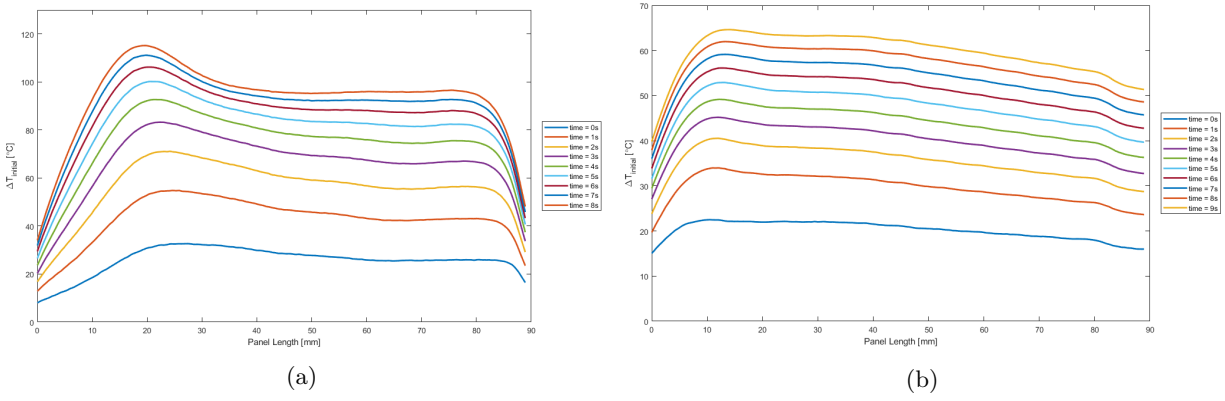


Figure 9: Temperature increase with respect to the pre-run wind-off temperature for a ramp angle of 35° for (a) the compliant ramp at $Re = 6.6 \times 10^6 \text{ m}^{-1}$ and (b) the rigid ramp at $Re = 23.7 \times 10^6 \text{ m}^{-1}$.

Acknowledgments

The authors would like to acknowledge Earl Dowell and Maxim Freydin for their assistance in determining the temperature for the onset of buckling for this panel.

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