Development of a Mechanical Stage Separation Mechanism for Two-Stage Sounding Rockets

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Stage separation of student-built multistage sounding rockets is often achieved using black powder charges. This method, however, can lead to undesirable separation dynamics and negatively affect second stage trajectories. To mitigate this potentiality, student members of Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club (RRC) at Georgia Tech, have developed a mechanical stage separation mechanism for their multistage sounding rockets. This paper highlights how, over a three-year development period, the system evolved from concept to final flight hardware and was flown twice on two-stage sounding rockets; once in 2022 and again in 2023. The system employs a Marman clamp separation system consisting of mated flanges held together by a spring steel band, tensioned with nylon cord. Separation of the band is initiated via a pyrotechnic line cutter. The present work presents an overview of the system, providing technical details and the story of the design process through concept, refinement, testing, and finally flight demonstration. Analysis and testing, along with demonstrated in-flight performance substantiate the effectiveness of the system, highlighting its potential for future development and use.

I. Introduction

In 2019 GTXR flew its award-winning two-stage rocket *Sustain Alive* at the Spaceport America Cup challenge in New Mexico.* That flight utilized a traditional black powder pyrotechnic staging mechanism to separate its sustainer and booster stages. In these systems, the two stages are mated via a coupler with shear pins. When ignited by an electronic match, a black powder charge within the coupler generates enough pressure to split the shear pins and sever the connection between coupler and sustainer. Residual pressure pushes the stages apart, leading to stage separation.

While extremely robust and effective, the violent detonation of black powder charges can lead to undesirable separation dynamics and cause oscillations in sustainer attitude, which can reduce apogee altitude. Attitude instability was observed after stage separation of *Sustain Alive*, thus, efforts began in fall 2019 to develop a mechanical staging system that would facilitate gentle separation of sustainer and booster stages. The system that was finally designed revolved around a Marman clamp system where the two stages of the rocket were held together by flanges, secured by a tensioned steel band and v-shaped blocks that press the two flanges together. This paper highlights the full design life cycle of this mechanism; including design, analysis, testing, and the results of its implementation on sounding rockets launched in 2022 and 2023.

II. Design and Analysis

Marman clamp systems see widespread use across the aerospace industry, most commonly in satellite and kick stage separation systems, such as those outlined in [1] and [2], and coupling of fluid devices. These systems also have flight heritage in collegiate rocketry, where a dual Marman clamp system was used as a separation mechanism for the payload module of TU Delft's *Stratos II+* sounding rocket [3]. The flight heritage of the Marman clamp system, and the fact that it allows for extremely low-shock stage separation in comparison to pyrotechnic methods made it an extremely appealing choice for implementation by GTXR.

A. Initial Design

The initial design of the system is shown in Fig. 1. The system consists of lower and upper flanges, which bolt into the booster and sustainer airframes, respectively. The mating surface of the flanges is a simple annular ring while

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*"2019 Spaceport America Cup" available via `https://spaceportamericacup.com/portfolio-item/2019-spaceport-america-cup/`

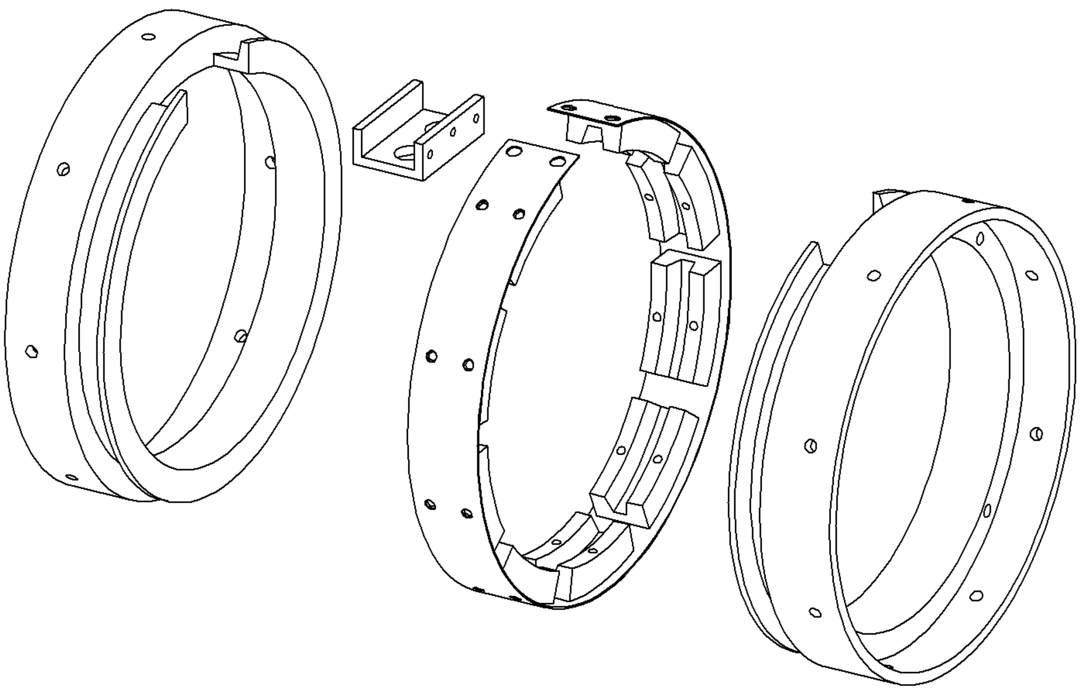


Fig. 1 Exploded view of initial mechanical staging design, from left to right: lower flange, clocking block, clamp band assembly, upper flange.

the upper surfaces of the flanges have a 15 degree angled surface, in accordance with recommendations in [4]. Eight v-shaped blocks, "v-blocks," squeeze into the v-shaped surface formed by the combination of the two flanges, clamping them together. The v-blocks are fastened to a 0.03 inch thick steel band, which is wrapped around the flanges and tensioned via nylon cord laced through four holes at the opening of the band.

A slot is cut in both flanges and a clocking block is fastened to the upper flange. This block keeps the upper and lower flanges in circumferential alignment and holds two Nichrome line cutters. These line cutters have small loops of Nichrome wire wrapped around the tensioned nylon cord. When current is provided to the Nichrome wire they heat up and melt through the nylon cord, releasing the band and allowing the two flanges to separate. The elastic potential stored in the band was sufficient to launch the band several feet from the flanges during testing, demonstrating extremely rapid de-coupling of the stages.

While the initial design of the staging mechanism showed promise, numerous concerns were raised during testing. First, tensioning and tying off the nylon cord by hand was found to be difficult and prone to user error; second, the Nichrome wires were found to be fragile and hard to properly secure; and finally, tests revealed that the sustainer would experience excessive angular displacement when the system was subject to bending loads, showing that it would fail its primary requirement of providing a rigid interface between the two stages.

B. Design Evolution

It was immediately clear that tensioning the clamp band had to be made more consistent and not reliant on user ability. A ratchet mechanism was briefly considered, but it was found to be too mechanically complex and difficult to manufacture. Instead, an elegant solution consisting of a simple eyebolt was designed. In the new design, the clocking block was eliminated altogether and instead of a large section being cut out of the flanges to accommodate the clocking block, four holes were drilled into the upper and lower flanges instead. The nylon cord is then threaded through these holes, into the lower flange, and tied to an eyebolt. The eyebolt is threaded into a block fastened in the lower staging flange and the cord is tensioned by simply screwing the eyebolt down through this block.

The Nichrome cutters were also done away with, instead being replaced by pyrotechnic Mako† line cutters. These are

† "The Mako Para Cord Cutter" available via `https://www.tinderrocketry.com/the-mako-cutter`

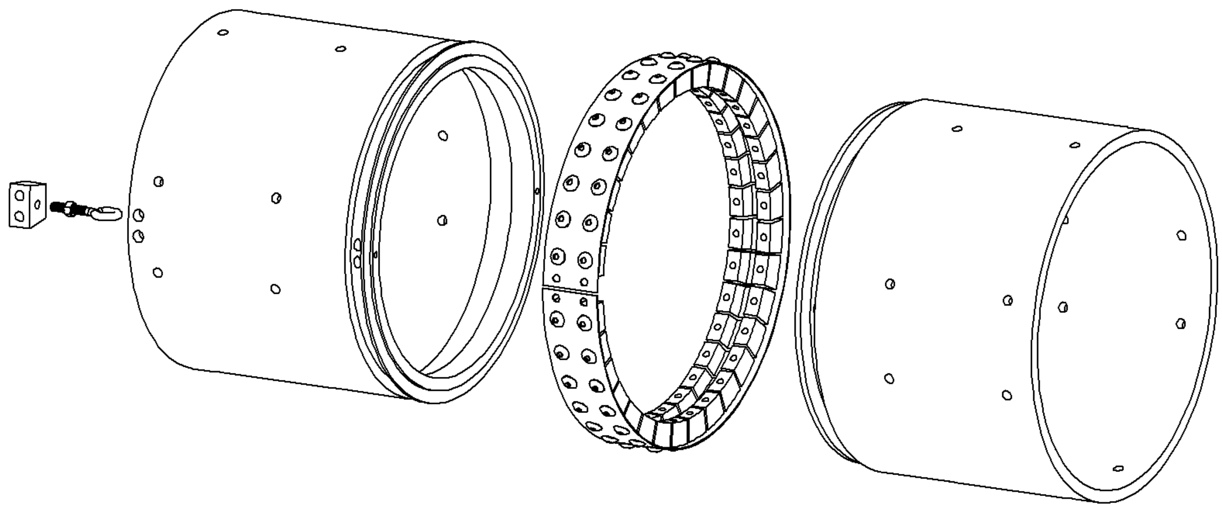
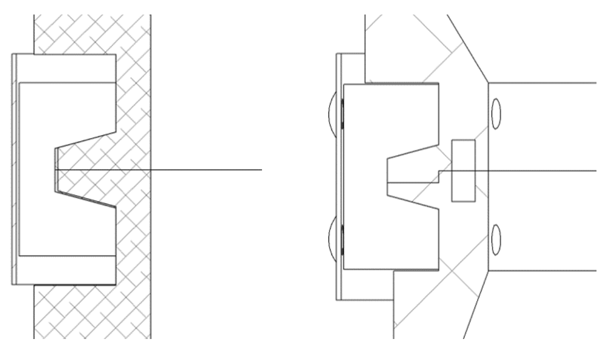


Fig. 2 Exploded view of final mechanical staging system design, from left to right: eyebolt mounting block and eyebolt, lower flange, clamp band assembly, upper flange.

much less fragile than the Nichrome circuitry, and can reliably cut the nylon cord with much less current than required for the activation of the Nichrome line cutters. Two Mako line cutters are used in the system, providing redundancy against actuation failure.

To make the system more resilient to bending loads, a shoulder was introduced on the mating surface of both flanges. The shoulder increases the contact area between the flanges and prevents lateral "sliding" motion of the flanges across the mating surface. Figure 3 demonstrates the difference in mating geometry between the initial (Fig. 3a) and final (Fig. 3b) designs. Additionally, the number of v-blocks was increased to 32 and the removal of the clocking block meant that greater circumferential coverage of the flanges by the v-blocks was possible. The length of the flanges themselves was also increased to greater resist bending at the bolted interface between the flanges and airframe itself. Figure 2 shows the final design of the system.



a) **b)**

Fig. 3 Comparison of a) initial and b) final mating surface designs.

C. Analysis and Testing

To validate the performance of the system under flight loads, simulation in ANSYS was performed to examine material stresses under compression loading. The simulations revealed that the system had a significant factor of safety under compression loads and yielding of the aluminum structure would not be a concern during flight.

The primary concern for structural stability thus remained bending loads. Analysis on simulation data for *Rubberband Man*, a two-stage rocket flown by GTXR in 2021, provided insight into the maximum bending loads that could be seen by the vehicle. From this analysis, the decision was made to test the system to 500 ft-lbf of bending moment across the staging flange. This represented a fourfold factor of safety over the maximum bending loads expected during *Rubberband Man*'s flight. The high factor of safety served to ensure the system would provide structural integrity during off-nominal flight or on later rockets experiencing more demanding flight regimes.

Figure 4 shows the testing setup, which consists of the staging system and lower airframe strapped to a stand, while an Instron load frame applies a force to a 30 inch section of airframe bolted to the upper staging flange. Testing results for six trials are shown in Fig. 5, demonstrating a maximum angular deflection of only 1.05 degrees at maximum loading, which was deemed sufficient for stable flight.

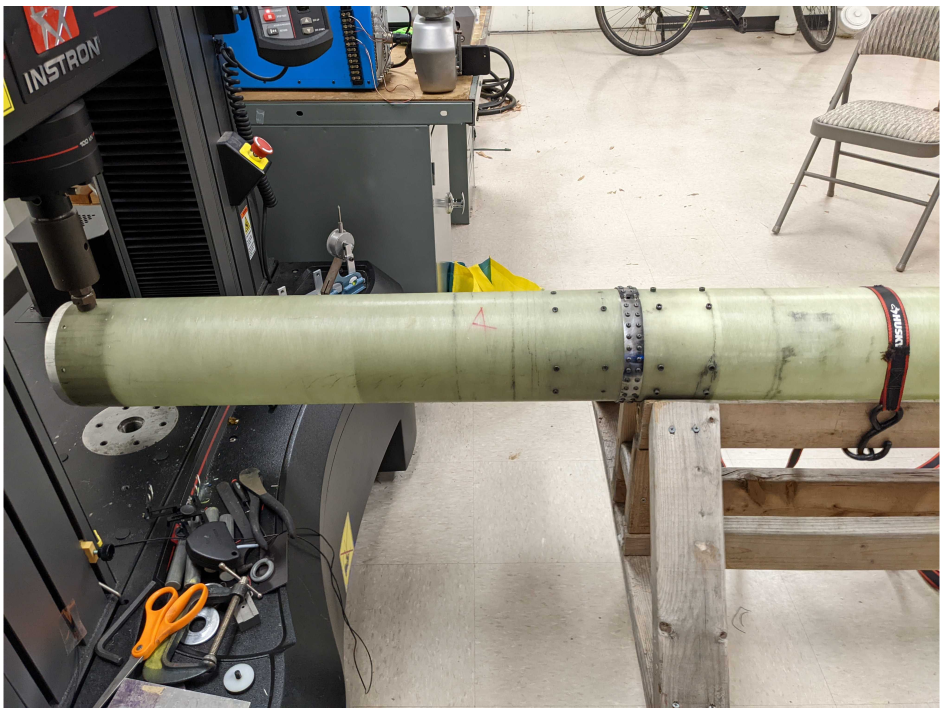


Fig. 4 Bending test setup.

III. Flight Testing

The mechanical staging system was validated in flight on two vehicles. The first, *Mr. Blue Sky* was a two-stage sounding rocket flown in the summer of 2022. The second, *Material Girl* was a similar two-stage rocket flown in the summer of 2023. On both flights the mechanical staging system maintained a solid mate between the two stages until stage separation, thus validating the mechanical design of the system. However, both vehicles experienced other anomalies which caused early or off-nominal actuation of the staging system. The following subsections explore these two launches and the performance of the mechanical staging system in greater detail.

A. 2022 *Mr. Blue Sky* Flight

The updated mechanical staging system was integrated into GTXR's *Mr. Blue Sky* for a summer flight in 2022. This two-stage rocket contained avionics in bays at the fore end of both the booster and sustainer, with the deployment of the mechanical staging band being initiated by the avionics in the booster. Shortly after ignition of the first stage motor,

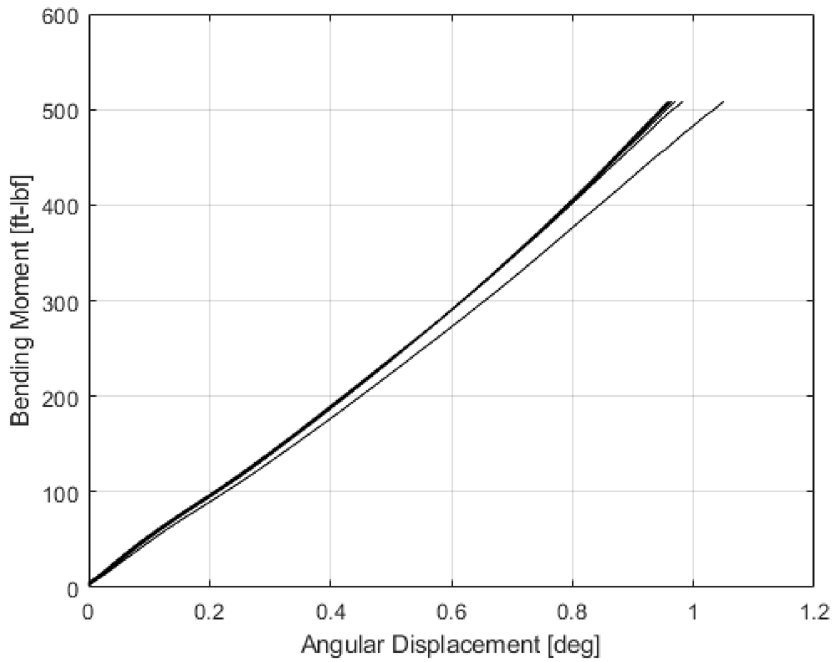
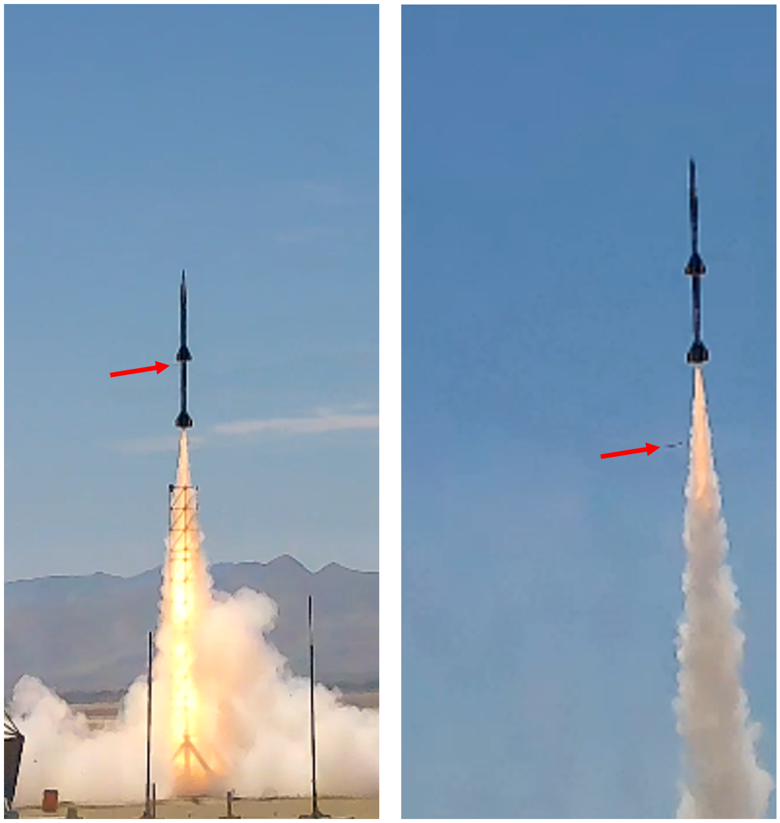


Fig. 5 Applied bending moment versus angular displacement of upper airframe for six Instron bending tests.

the staging band was observed being jettisoned from the vehicle, as shown in Fig. 6. Telemetry analysis revealed that premature activation of the Mako line cutters by the flight computer may have been responsible for the early deployment of the staging band.

Despite the loss of the clamp band, the two stages remained in contact through the duration of the first stage burn due to the extreme compression loads across the mating interface, which resisted bending moments aided by the inclusion of the shoulder in the flanges. The stages only separated as the first stage thrust tapered out and drag on the larger first stage fins dominated, facilitating separation of the stages.



a) b)

Fig. 6 Images of premature clamp band deployment during liftoff of *Mr. Blue Sky*: a) initial band release and departure from vehicle b) band falling away from ascending vehicle.

B. 2023 *Material Girl* Flight

In July 2023, the mechanical staging system was flown on another two-stage GTXR rocket, *Material Girl*. The design of the vehicle was superficially similar to *Mr. Blue Sky*, but included redesigned internal components for more assured vehicle recovery [5], a simplified avionics stack with all active components located in the sustainer, and overall weight savings meant to increase the target apogee. The mechanical staging system had no major changes save the lengthening of the lower flange and the upper flange being pinned directly to the sustainer motor rather than the sustainer fin can as it was on *Mr. Blue Sky*.

Material Girl flew off a launch rail provided by FAR, rather than GTXR's custom launch rail. This rail only supported the booster of the vehicle, while the sustainer was solely supported by rigidity of the mechanical staging interface. Thus, the operation of the system for its second flight included higher pre-flight loads while the launch rail was horizontal. Though testing had shown that the system would be able to support the mass of the cantilevered sustainer, blocks were placed between the sustainer and the rail to alleviate the loading of the staging system, and combat the possibility of creep within the tensioning cord. Despite this effort, the rocket had to be removed from the launch rail and the staging band re-tensioned once before flight.

Reference [6] provides an overview of the *Material Girl* rocket and its flight. The vehicle launched in the morning of Saturday, July 8th, 2023, and immediately experienced anomalies; the following major events were observed:

1) **T+00:00** booster ignition, shown in Fig. 7a
2) **T+00:01** flight computer erroneously deploys nosecone and sustainer parachutes, shown in Fig. 7b
3) **T+00:02** vehicle clears the launch rail and achieves stable flight without nosecone
4) **T+00:05** sustainer motor ignites during first stage boost
5) **T+00:05** sustainer and booster separate and trajectories diverges, shown in Fig. 7c
6) **T+00:37** sustainer apogee of 31,000 ft

7) **T+01:10** sustainer impact

The flight once again demonstrated the mechanical staging system's ability to keep the two stages of the vehicle rigidly attached, resisting all flight loads imposed upon it. Once again, however, the actuation of the system was off-nominal, as stage separation was initiated early through erroneous activation of the sustainer motor by the flight computer resulting in hot staging and premature separation of the two stages. Despite the state of the vehicle at staging and the violence of the hot staging event itself, the mechanical staging system was recovered intact, including the staging band, which presumably actuated when the sustainer ignition plume burnt through the nylon tensioning cord, releasing the band.

a) **b)** **c)**

Fig. 7 Images of key flight events during liftoff of *Material Girl*: a) booster ignition b) premature nosecone deployment and c) sustainer hot staging. Courtesy of Casey Wilson.

IV. Conclusion

From initial design in 2019 and 2020, to major updates, analysis, and testing in 2021 through 2022, and finally flight testing in 2023 and 2024, the GTXR mechanical staging system has been proven to be a reliable method to rigidly mate stages of multistage sounding rockets. It's important to note that while the system has not experienced any failures during testing, it has yet to undergo a nominal flight test under expected conditions. Therefore, its true performance under operational flight conditions remains to be proven conclusively. Nonetheless, analysis and flight experience has shown that the system is capable of withstanding flight loads. The system is a departure from pyrotechnic-based staging systems, with the benefit of gentle separation dynamics. The mechanical staging system holds significant potential to be flown on future GTXR missions, serving as a stage separation mechanism or as a deployment mechanism for payload modules housing equipment sensitive to the violent forces associated with pyrotechnic deployment. Continued testing and refinement will further validate its capabilities and pave the way for its broader utilization in the future.

Acknowledgments

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