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Design and Use of a Guided Weight Impactor to Impart Barely Visible Impact Damage

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Abstract

The Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) is a concept that was developed by The Boeing Company to address the complex structural design aspects associated with a pressurized hybrid wing body (HWB) aircraft configuration, which has been a focus of the NASA Environmentally Responsible Aviation Project. The NASA-Boeing structural development for the HWB aircraft culminated in testing of the multi-bay box, which is an 80%-scale representation of the pressurized center-body section. This structure was tested in the NASA Langley Research Center Combined Loads Test System(COLTS) facility. As part of this testing, barely visible impact damage was imparted to the interior and exterior of the test article to demonstrate compliance with a condition representative of the requirements for Category 1 damaged composite structure as defined by the Federal Aviation Regulations. Interior impacts were imparted using an existing spring-loaded impactor, while the exterior impacts were imparted using a newly designed, gravity-driven impactor. This report describes all of the impacts to the test article, but is primarily focused on the design and use of the gravity-driven guided-weight impactor. The guided-weight impactor proved to be a very reliable method to impart barely visible impact damage in locations that are not accessible for a traditional drop weight impactor, while at the same time having the capability to be highly configurable for use on other aircraft or spacecraft structures.

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Introduction

The Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS)[1] is a concept that has been developed by The Boeing Company (Boeing) to address the complex structural design aspects associated with a pressurized hybrid wing body (HWB) aircraft configuration as shown in Figure 1. The HWB has been a focus of the NASA Environmentally Responsible Aviation (ERA) Project, with structural development primarily addressing the pressurized, non-circular fuselage portion of the HWB. PRSEUS is an integral structural concept whereby skins, frames, stringers, and tear straps are all stitched together, then infused and cured in an out-of-autoclave process. The PRSEUS concept, as it has been applied to pressurized HWB fuselage structure, is shown in Figure 2. The concept has evolved from stitching technology development activities in several NASA-Boeing and Air Force Research Lab (AFRL)-Boeing programs beginning in the 1990's.[2-5] The key to the PRSEUS concept is the pre-cured, pultruded rod that is contained within the stringer wrap plies and which passes through the frames, providing an uninterrupted load path through the acreage in the stringer direction. At the same time, the full height frame stiffener is also continuous, except for the keyhole through which the stringer passes, providing an uninterrupted load path in the direction perpendicular to the stringer. These efficient structural stiffening members provide the majority of the panel stiffness, permitting the use of minimum skin thickness for many applications. For example, typical PRSEUS stringer and frame cross-sections examined for HWB fuselage-type structure are shown in Figure 3, where the skin is minimum gage and the stringer and frame are the main load carrying components.[6,7] Minimum gage is a stack of 9 layers of carbon/epoxy material that is 0.052 inches thick. Typical stringers in the HWB design use only a single stack for the stringer, which creates a two-stack web and single-stack wrap around the rod at the top of the stiffener.

Throughout ERA, the building block approach has been used to design, analyze, build, and test HWB PRSEUS structural components leading to an 80%-scale center portion of the HWB as shown in Figure 4 and identified in the lower right portion of the figure by the shaded region. Testing of the 80%-scale Multi-bay Box (MBB) in the Combined Loads Test System (COLTS) Facility at NASA Langley Research Center (LaRC)[8,9] began in April 2015. The MBB was subjected to a series of load cases with testing being concluded in May after the infliction of discrete source damage to the top of the test article. A photograph of the test article between the platens in the COLTS Facility and a graphical representation of the COLTS arrangement are shown in Figure 5. Actuators connected to the platens are used to apply mechanical loads to the test article. Pressure loading was applied using a high-pressure feed line that was connected to the MBB. Five loading condition combinations were applied to the pristine MBB in a series of experiments, first up to design limit load (DLL) and then up to design ultimate load (DUL) levels for each condition. These loading conditions were 1) an internal pressure load alone; 2) a load simulating a 2.5-g wing up-bending condition which subjects the crown panel to compressive loads; 3) a -1-g wing down-bending condition which subjects the crown panel to tensile loads; 4) a combination of pressure and -1-g wing down-bending; and 5) a combination of pressure and 2.5-g wing up-bending. Details of the testing, load conditions, and results are presented in Refs. 10-12. Included within the testing was a repeated set of the five load conditions after barely visible impact damage (BVID) was introduced. BVID was introduced to satisfy conditions representative of the requirements in the Federal Aviation Regulations (FAR) requirements, PART 25-Airworthinesss Standards: Transport Category Airplanes),[13] which is summarized in Ref. 14. The requirement is that composite structures with Category 1 damage, including BVID, shall demonstrate a reliable service life while retaining ultimate load capability. How BVID was imparted to the MBB and the development of a guided drop weight impactor that was used to impart BVID to the exterior of the MBB is described in the current report.

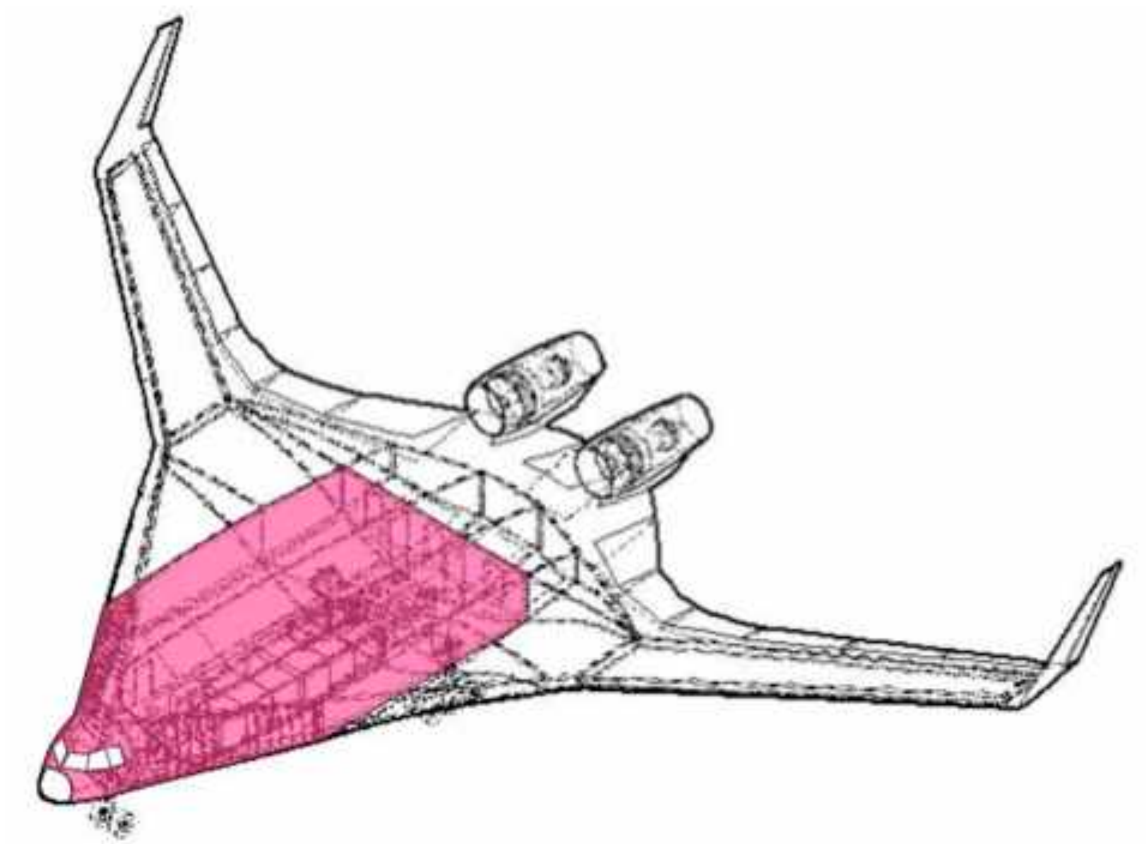


Figure 1. Typical pressurized portion of a HWB aircraft concept, indicated by red shaded area.

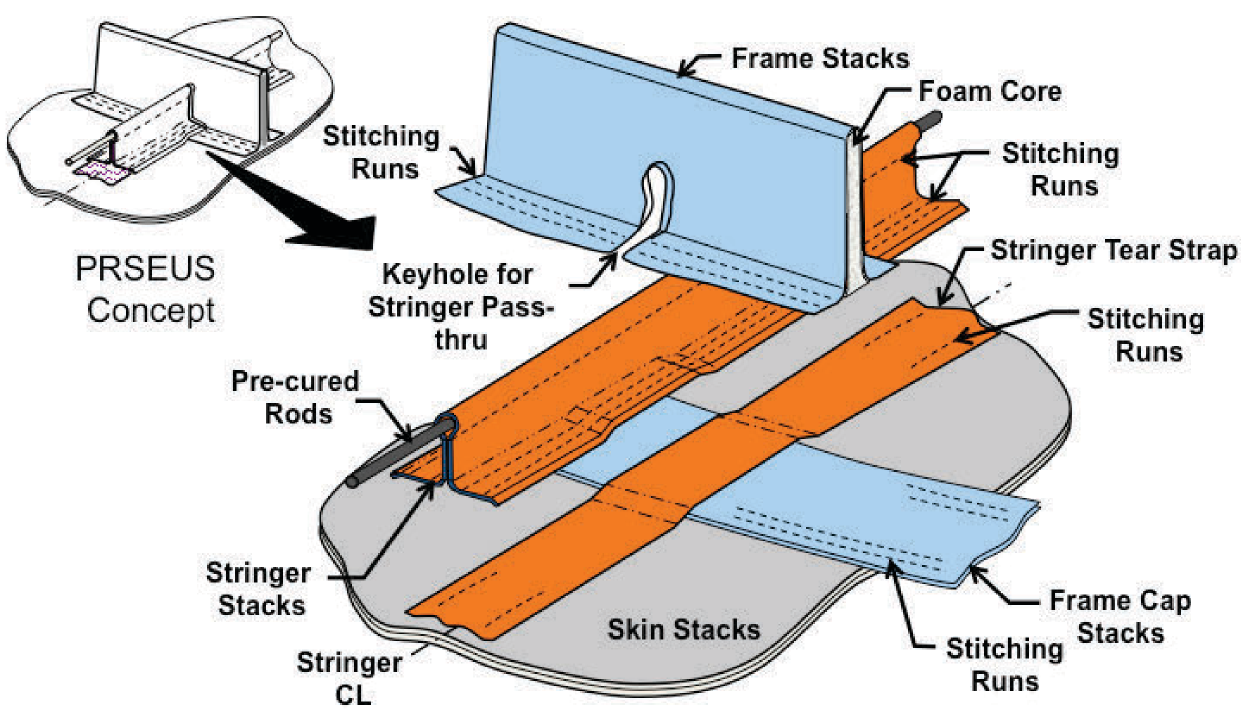


Figure 2. Typical PRSEUS concept.

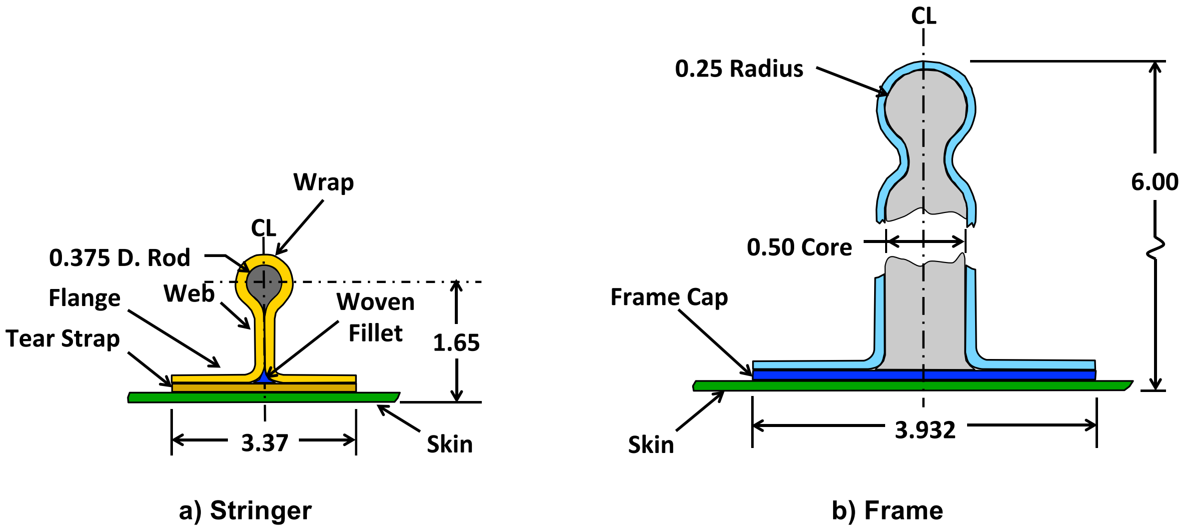


Figure 3. Typical pressurized HWB fuselage frame and stringer cross-sections. Dimensions are in inches, and typical stack values are shown for stringer.

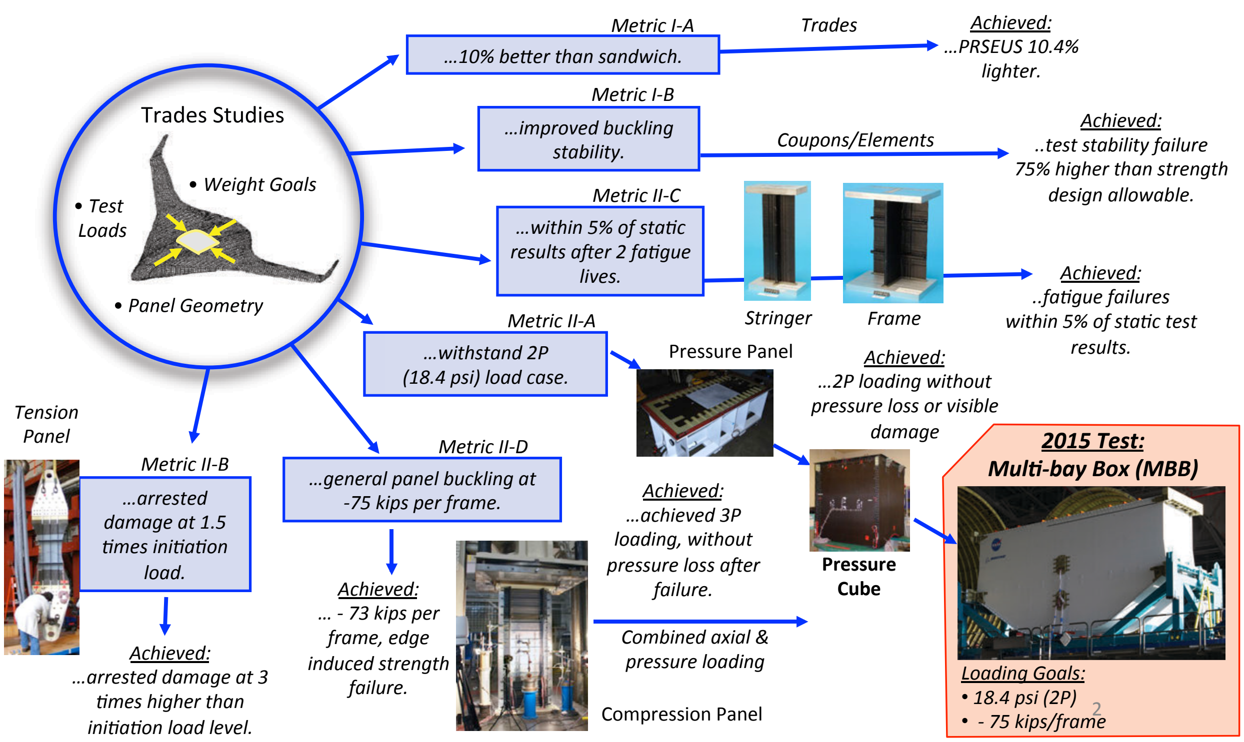


Figure 4. HWB structural development building-block approach.

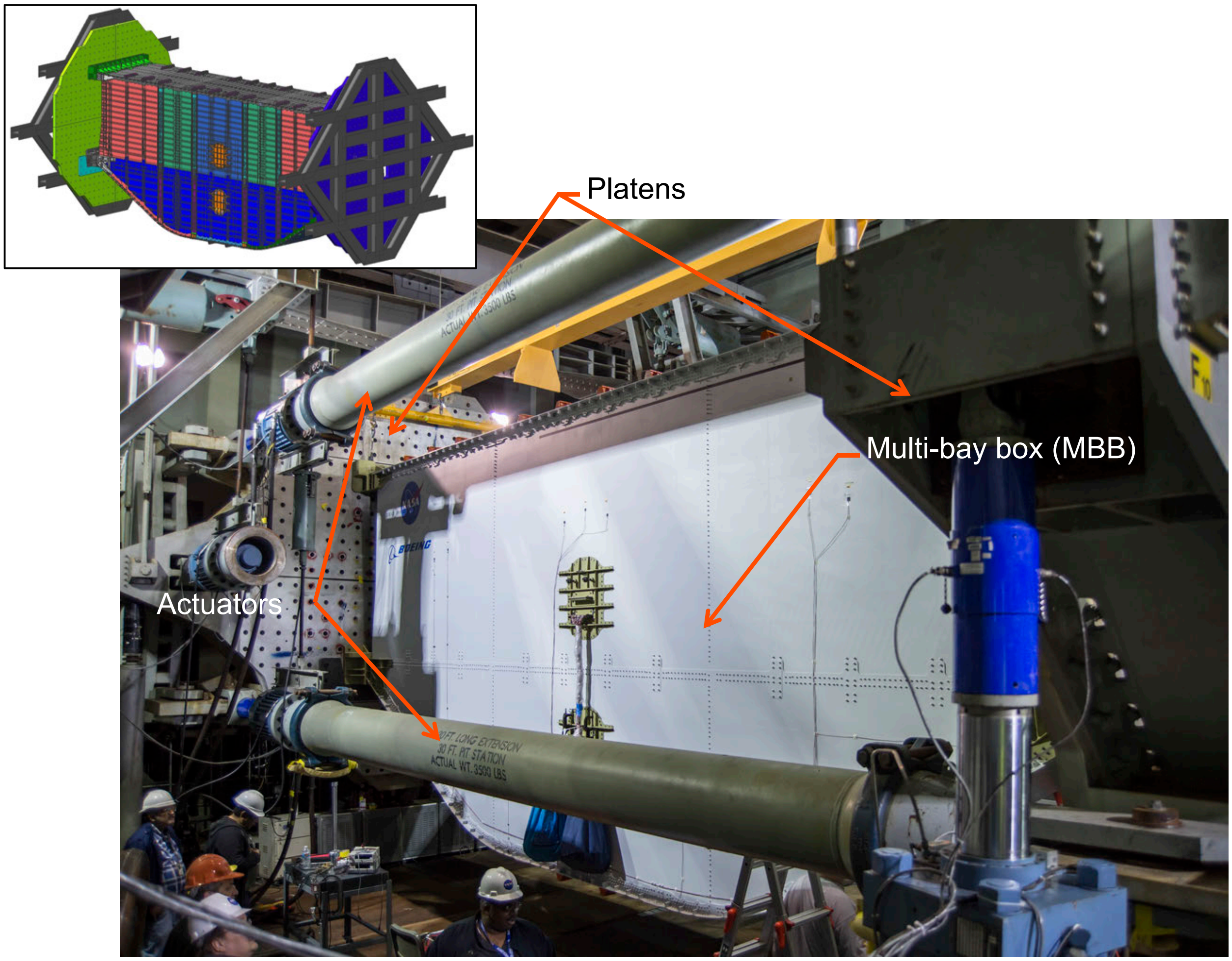


Figure 5. Photograph of MBB in COLTS test chamber and graphical representation (inset).

Impact Requirements

To satisfy conditions representative of the BVID requirements,[13,14] the MBB had to be impacted with energy levels sufficient to impart BVID, but with an energy level not to exceed maximum values for interior and exterior impacts of 20 ft-lb and 100 ft-lb, respectively. In order to determine energy levels that were below the maximum values, which would result in BVID to various locations within the MBB PRSEUS structure, a series of tests were carried out at Boeing and LaRC. For interior impacts, it was determined that a 15 ft-lb energy level would result in BVID on the skin, and that the top of the stringer and frame could withstand the maximum 20 ft-lb level. For exterior impacts, it was determined that the skin would show BVID with the 15 ft-lb level, while the stringer and frame flanges would exhibit BVID at 50 ft-lb and 60 ft-lb levels, respectively. A summary of the required impacts for the MBB is provided in Table 1, and the corresponding impact locations are identified and their locations on the MBB are shown in Figure 6. Exterior impacts at the stringer and frame flanges means impact of the skin that is backed by the flanges, giving the thicker skin/flange region as seen in the figure. The interior impacts would be conducted using an existing 3.708 lb weight, while the exterior impacts would use a 5-lb weight for the 15 ft-lb energy and a 15-lb weight for the 50 ft-lb and 60 ft-lb energies. Lastly, the impact weight indentor, or tup, was required to follow standard practice and have a 1-inch hemi-spherical shape.

Interior impacts were performed using the portable spring-loaded impactor that was used for impacts on the composite crew module.[15] This impactor was chosen as it has been demonstrated as suitable for the appropriate impact levels on numerous composite structures, including a PRSEUS pressure panel.[16] The impactor was calibrated through various trial runs, and then used to apply the interior BVID impacts to the MBB as described in Reference 17. However, due to multiple constraints regarding the exterior impacts, a new impactor had to be designed to impact the MBB. The design process is described in the Guided-Weight Impactor Design section, and use of this new impactor to impart BVID to the MBB is described in the Exterior Impacts section.

Table 1. Summary of MBB impact locations, energy, and velocity.

Interior - Upper Forward Bulkhead				
ID	**Description**	**Energy (ft-lb)**	**Weight (lb)**	**Velocity (ft/s)**
I1	Frame Top	20	3.708	18.63
I2	Stringer Top	20	3.708	18.63
I3	Center Skin Bay	15	3.708	16.14

Exterior - Keel				
ID	**Description**	**Energy (ft-lb)**	**Weight (lb)**	**Velocity (ft/s)**
E1	Frame Flange	60	15	16.04
E2	Stringer Flange	50	15	14.65
E3	Center Skin Bay	15	5	13.89

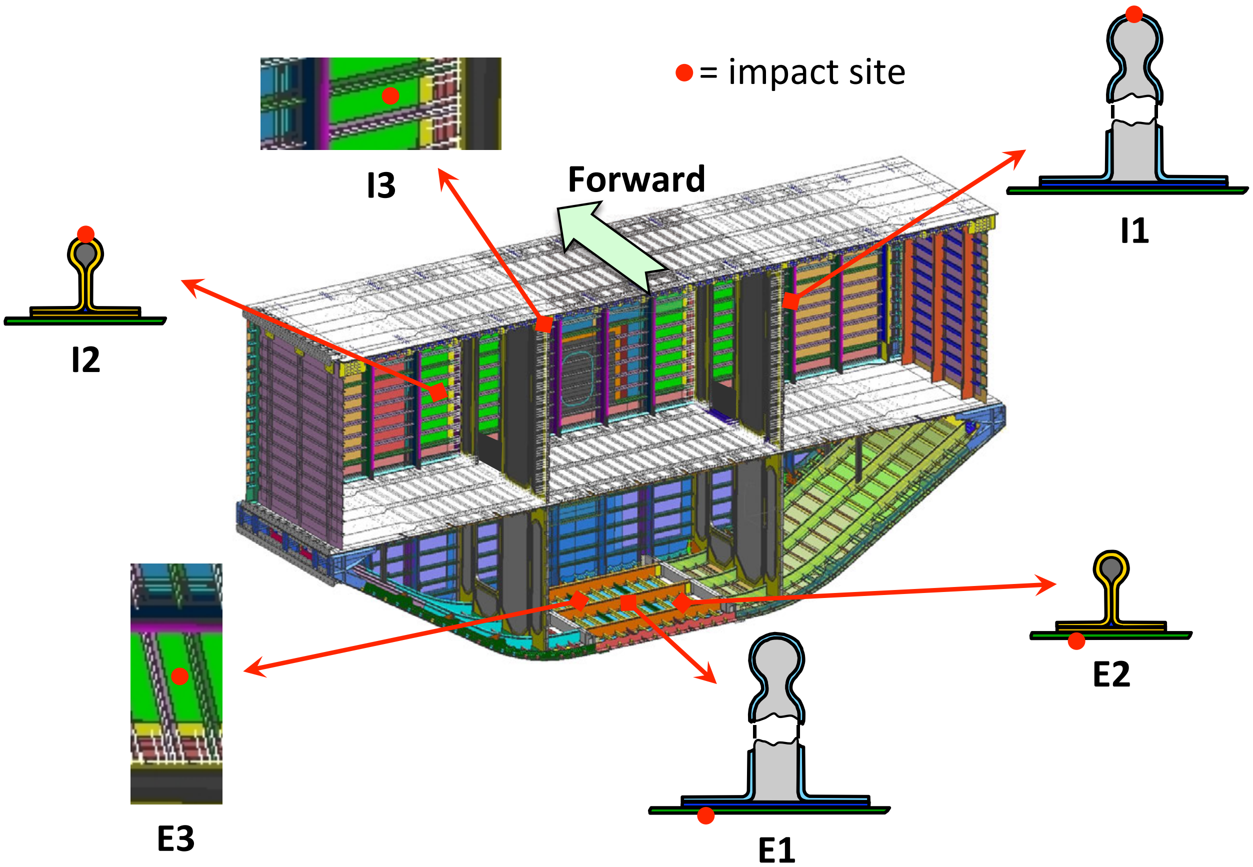


Figure 6. MBB impact locations (aft bulkhead removed for clarity).

Guided-Weight Impactor Design

The exterior impacts required heavier impact weights than the interior impacts, and with the exception of the minimum gauge skin required higher energy levels. Specifically, the requirement was that the skin impact be imparted using a 5-lb weight, and the frame and stringer flange impacts be imparted using a 15-lb weight. Traditionally, large weights are used in a drop weight impactor, whereby gravity accelerates the weight to obtain the correct impact energy, and the impact damage is imparted to the top surface of the test article. Such a method has been used on numerous structures including the curved PRSEUS panel tested at the Federal Aviation Administration (FAA) testing facility[18] and the PRSEUS Cube tested at NASA LaRC.[6,7] In the case of the Cube, the test article was rotated on its side, so that the impact site was oriented upward to facilitate the use of the drop weight impactor. However, the exterior impacts on the MBB were imparted to the center keel, or the underside of the MBB. Unfortunately, the MBB could not be rotated to orient the impact sites upward as was done with the Cube. Therefore, a device was needed that could be used to impact the center keel with the impact weight moving upwards at impact, while at the same time restraining the motion of the impact weight to ensure impact occurred at the desired location. In order to impact in this manner, a design study was undertaken to develop a means of easily and reliably imparting BVID to the center keel.

Numerous methods were available to propel the impact weight upwards at impact. Methods considered included gas-propelled weight, spring-propelled weight, gravity-driven pendulum, gravity-driven pulley/weight system, gravity-driven teeter totter, and a gravity-driven guided drop weight. A primary driving factor in the design of the impactor was the constrained distance between the center keel and the floor of COLTS, which was only about 38 inches. This short distance would require any gas or spring propelled weight, which for this type of impactor is usually constrained to straight-line motion, to accelerate very rapidly over an extremely short distance. Consider that the weight would have some reasonable length, say 6 inches, and the spring would be an additional distance of 6-12 inches. The weight acceleration length would be no greater than 24 inches since there should be some travel distance without force being applied by the spring. During this unforced distance, gravity would be acting against the weight, meaning that the velocity at the point of loss of contact with the spring would have to be even higher than the velocity required at impact. A similar problem exists with a gas propelled weight as there is still the need for travel without pressure driving the weight, but since it may be possible to use a shorter distance to form the initial pressure volume, the distance available for accelerating the weight might be slightly higher, a maximum of approximately 29 inches. Additionally, with the limited prelaunch volume available for the spring and gas, the spring constant and the pressure level would be large, and slight changes in weight position could lead to too significant variation in the final velocity at impact. The limited acceleration distance, combined with the variability in velocity expected to be seen with spring and gas propelled weights, eliminated these methods as an option. Therefore, a gravity-driven design was chosen to be the most repeatable and reliable method of imparting energy to the weight for the impacts.

A pendulum device was considered, but was eliminated due to the short height between the keel and the floor. Since an impact was required near the center of the center keel, the impactor had to be able to reach that location on the MBB, which was a similar distance as the distance between the keel and the COLTS floor. This dimensional constraint made a pendulum device incapable of providing the required motion for impact. Another gravity-driven impactor that was considered and eliminated was a pulley system design that used a dropped weight to impart motion to the impact weight. The pulley design system was also constrained by the need to rapidly accelerate the impact weight in the very limited height. This option was deemed to be too complex, both in terms of the pulley system required to convert the downward motion of the dropped weight into the appropriate upward motion of the impact weight and in constraining the path of the impact weight for accurately impacting the correct location. The teeter totter design was eliminated primarily with difficulties that again arise from the constrained space between the keel and COLTS floor. If the whole apparatus was to fit in this space, the dropped weight that would propel the impact weight via the teeter totter motion would have to be large to accelerate the impact weight in the short distance. A small error in dropped weight height would lead to large errors in the impact energy. On the other hand, a teeter totter could be made sufficiently long to permit a higher drop with a lighter dropped weight that was located outside the planform of the MBB. The resulting long teeter totter would have to be excessively stiff to not have significant deformations and slingshot motions, which is impractical. Therefore, the guided drop weight impactor was selected, designed, built, and used to impart BVID to the MBB exterior.

The guided drop weight impactor is a gravity-driven system that was designed using the following set of requirements:

- Accommodate impact weights of 5-lb and 15-lb.
- Have a 1-inch hemi-spherical tup.
- Must be constrained at impact to ensure desired orientation and location at the time of impact.
- The maximum required exterior impact velocity shown in Table 1 must be achievable, while accounting for potential energy loss due to friction or other sources.
- Must be able to be positioned in COLTS to produce BVID at the required locations.

As designed, the guided drop weight impactor consists of two main components, namely the guided impact weight and the guide track. This configuration is similar to a roller coaster, whereby gravity provides the driving force on the coaster, whose motion is controlled by the configuration of the track. The impact weight runs along the track and is constrained at impact to be moving in the required direction, which for the MBB was vertically. To satisfy the two required impact weight values, design of the impact weight resulted in a baseline 5-lb impact weight that is configurable to 15-lb by adding weight blocks. The two configurations used to impact the MBB are shown in Figure 7. An expanded view of the 5-lb impact weight with components labeled is shown in Figure 8, with a listing of components provided in Table 2. An expanded view of the 15-lb impact weight with components labeled is shown in Figure 9, with a listing of components provided in Table 3. The impact tup is attached to the base weight using a threaded stud, so that if desired, the shape of the impact tup can be changed to a different geometry. Two sets of 4 wheels are attached to each of the wheel brackets to guide the weight on the track. Flanged load runners were used as the wheels to help keep the weight centered on the track while it was rolling. The wheel brackets are attached to the base weight using four bolts and spacers (which in the 15-lb configuration are replaced by two of the added weights) that position the wheels at the proper width for the track. Tabs on the wheel brackets, adjacent to each of the wheels, ensure that at no time can the weight be ejected off the track, enabling the weight to only exit the track at the ends. In order to ensure that the baseline impact weight was 5 lbs, the remainder of the components were designed and chosen such that their total weight was just under 5 lbs. A weight adjustment screw was added on the aft end of the base weight, opposite the impact tup, by which washers or other small weights could be added to tune the total weight to the required 5 lbs. The 15-lb version of the impact weight was similarly tuned to the required weight. In fact, the configurable design actually enables the impact weight to be configured to any value of 5 pounds or greater, provided that the added weights don't interfere with the track or other components. Drawings for the manufactured parts of the guided weight are provided in Appendix A.

The track, shown in Figure 10, consists of two portions, namely the main track and the capture track, and is approximately 12-ft long, 3-ft wide, and 10-ft tall. The main track provides the height required to impart the necessary energy level. However, a portion of the main track works with the capture track to constrain the motion of the weight at the end of the track during impact. The capture track restrains the weight at impact by holding the weight against the main track, to guide the weight to the correct location at impact. As utilized on the MBB, the track was configured to have the impact weight traveling vertically upward at impact, however, the track could be configured to have impact imparted at nearly any angle away from vertically downward. For example, the track could be configured to impact normal to a circular fuselage at the 45-degree location, as measured from the keel of the fuselage towards the side. Depending on the impact energy and the structural response to the impact, it may be necessary to capture the weight (or insert a protective element such as a paddle) after initial impact to avoid a secondary impact event. As the angle moves away from vertically upward, the need to capture the weight after applying the required impact increases in order to eliminate the chance for double impact. The track is mounted to a base, and is supported in the area of the capture track and the areas of high force, such as where the weight is changing direction along the curved portion of the track adjacent to the base, by a plate to provide a more rigid track. Six off-the-shelf casters with rubber wheels are mounted on the base to allow for ease of movement of the track. The casters also have rubber supports/levelers that can be lowered in order to raise the wheels off the ground, to level the track base, and to help prevent movement of the track assembly while the impacts are being applied. The track base was assembled from off-the-shelf extruded aluminum bars, and the support braces were steel angles and straps. Drawings for key manufactured parts of the track are provided in Appendix B.

Calibration of the guided drop weight impactor was performed by impacting a wooden mock-up of the keel from various heights for each of the two weight configurations, and by measuring the velocity at impact using high-speed cameras. The setup is shown in Figure 11, where the impact area is seen in the center of the image. The impact area consists of two removable pieces of plywood that can be replaced as needed when they become damaged, and which were held in place on the mock-up using u-bolts. Phantom high speed cameras from Vision Research were located on both sides of the impact area (only one camera visible in the Figure 11), and the associated software provided with the cameras was used to calculate the velocity at impact.[19] An example screen capture from one of the calibration trials for the 5-lb weight is shown in Figure 12. To ensure consistency in the velocity measurement process, bowtie markers were added to both sides of the impact tup, and scales were added to the capture track support, as identified in the figure. The bowtie marker was used to provide a consistent point to measure, and the scale was attached to the capture track support in a plane that was perpendicular to the camera axis, and which contained both the scale and the bowtie marker. The removable wood impact sample was used to provide a fresh surface for the impacts, which also enabled development of the alignment process by examining the location of each impact compared to the target location that had been drawn onto the wood. An example of the wood after an impact is shown in Figure 13, where it can be seen that the impactor could be aligned to impact the proper location with very good accuracy, within about a sixteenth of an inch. After calibration for each impact energy, the track was marked to indicate the weight release location for performing the impacts to the MBB.

Table 2: 5-lb impact weight components.

a) Produced parts

ID	Part	Drawing #	Material	Quantity
A	Impact Tup	N/A	Steel	1
C	Central Block	RCI0007	Aluminum	1
D	Car Wheel Bracket	RCI0008	Aluminum	2

b) Purchased parts

ID	Part	Quantity
B	Threaded Stud, 1/2"-13, 2.25" length	1
E	Load Runner with Flange (Osborn Part# FLR-1 W/H)	8
F	Bolt, 1/4"-20, 4.0" length	4
G	Nut, 1/4"-20	4
H	Washer, 1/4" ID	16
I	Socket Cap Screw, 1/4"-20, 1.0" length	1
J	Washer, 1/4" ID (weight tuning)	As needed
K	Unthreaded Zinc-coated Steel Spacer	8

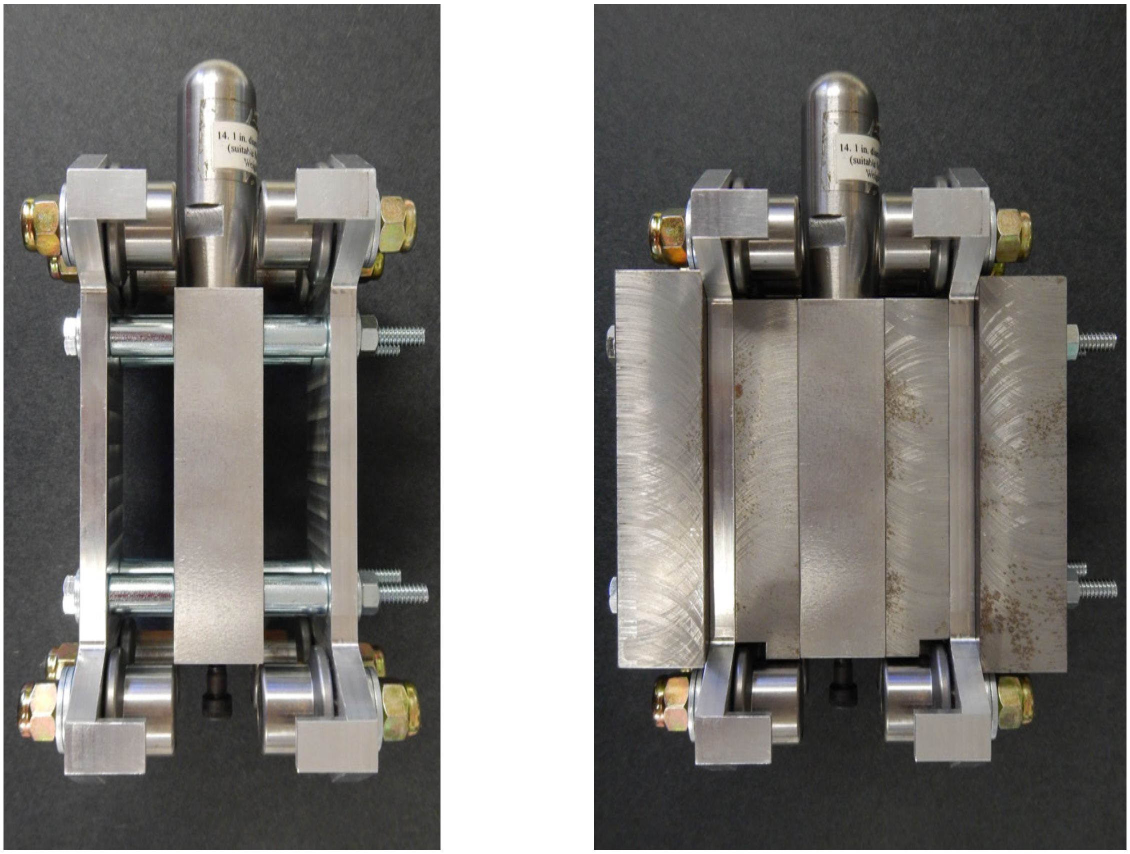
Table 3: 15-lb impact weight components.

a) Produced parts

ID	Part	Drawing #	Material	Quantity
A	Impact Tup	N/A	Steel	1
C	Central Block	RCI0007	Aluminum	1
D	Car Wheel Bracket	RCI0008	Aluminum	2
K	Weight Block #1	RCI0009	Steel	2
L	Weight Block #2	RCI0010	Steel	2

b) Purchased parts

ID	Part	Quantity
B	Threaded Stud, 1/2"-13, 2.25" length	1
E	Load Runner with Flange (Osborn Part# FLR-1 W/H)	8
F	Bolt, 1/4"-20, 6.0" length	4
G	Nut, 1/4"-20	4
H	Washer, 1/4" ID	8
I	Socket Cap Screw, 1/4"-20, 1.5" length	1
J	Fender Washer, 1/4" ID, 1.0" OD (weight tuning)	As needed
H	Fender Washer, 1/4" ID, 1.0" OD	16



a) 5-lb **b) 15-lb**

Figure 7. Pictures of the two configurations of the impact weight used to impact the MBB.

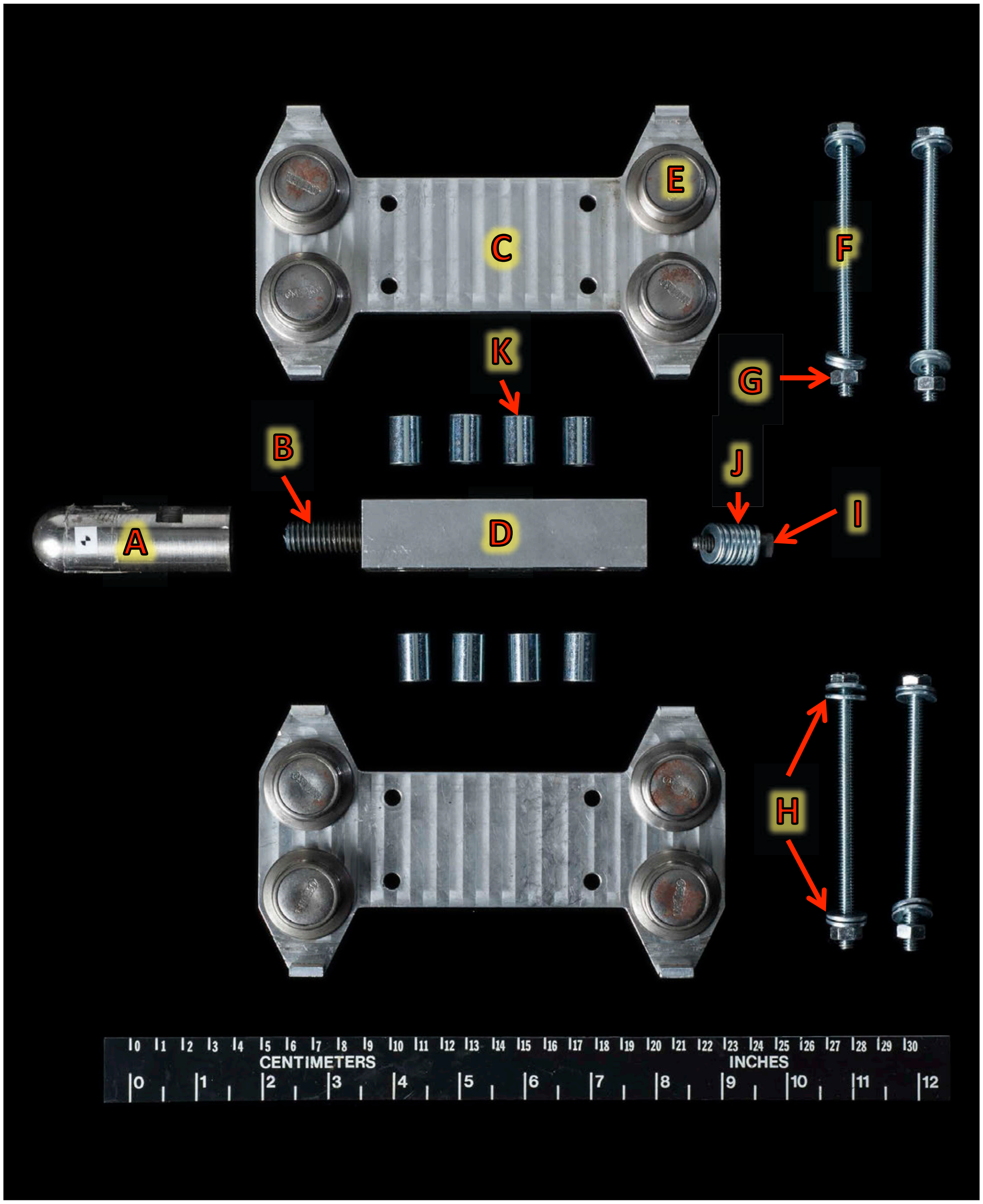


Figure 8. Expanded view of the 5-lb impact weight components.

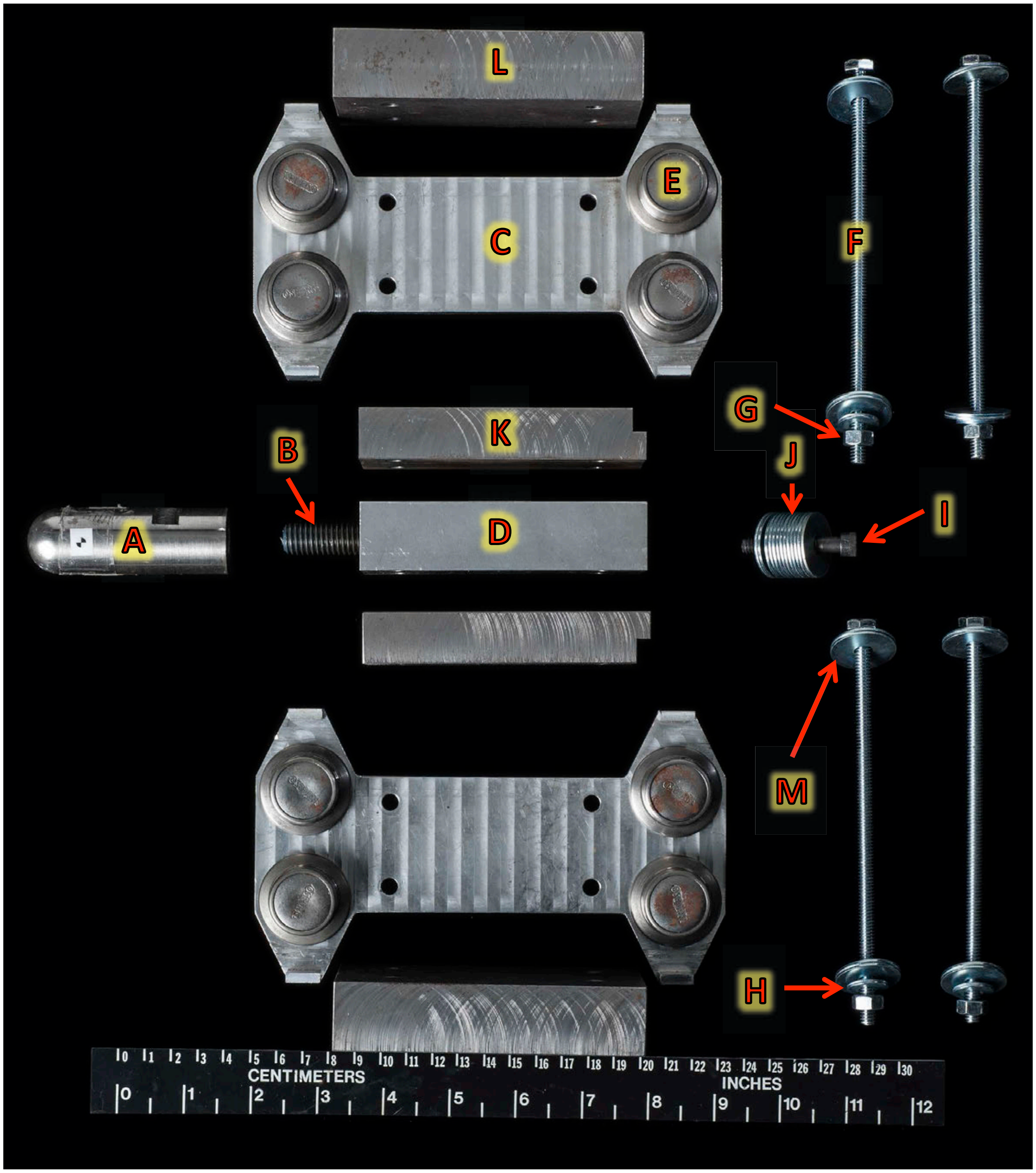
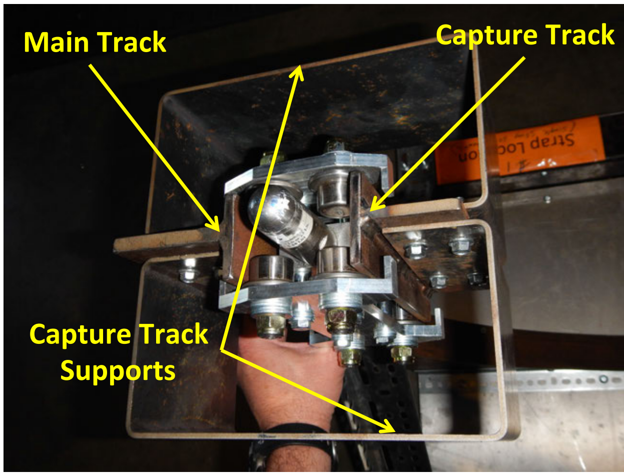


Figure 9. Expanded view of the 15-lb impact weight components.

Impact Capture Area



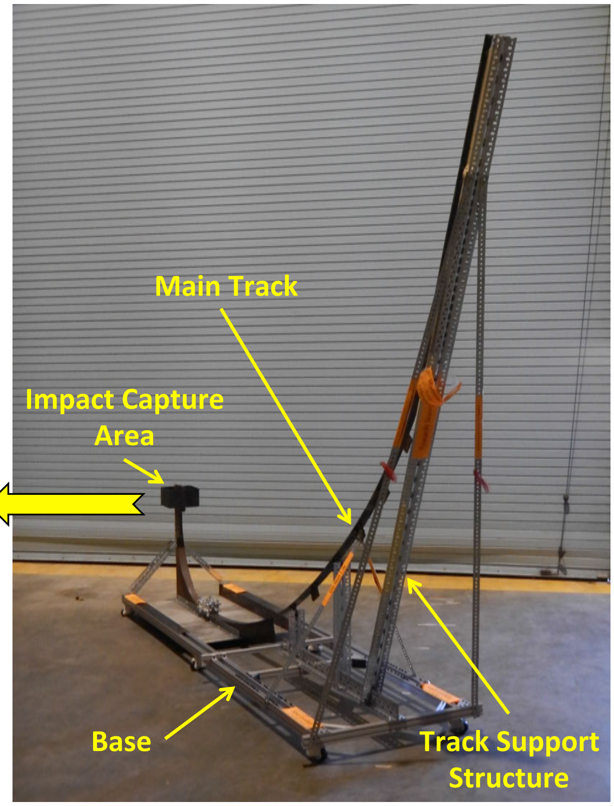


Figure 10. Guided weight impactor track.

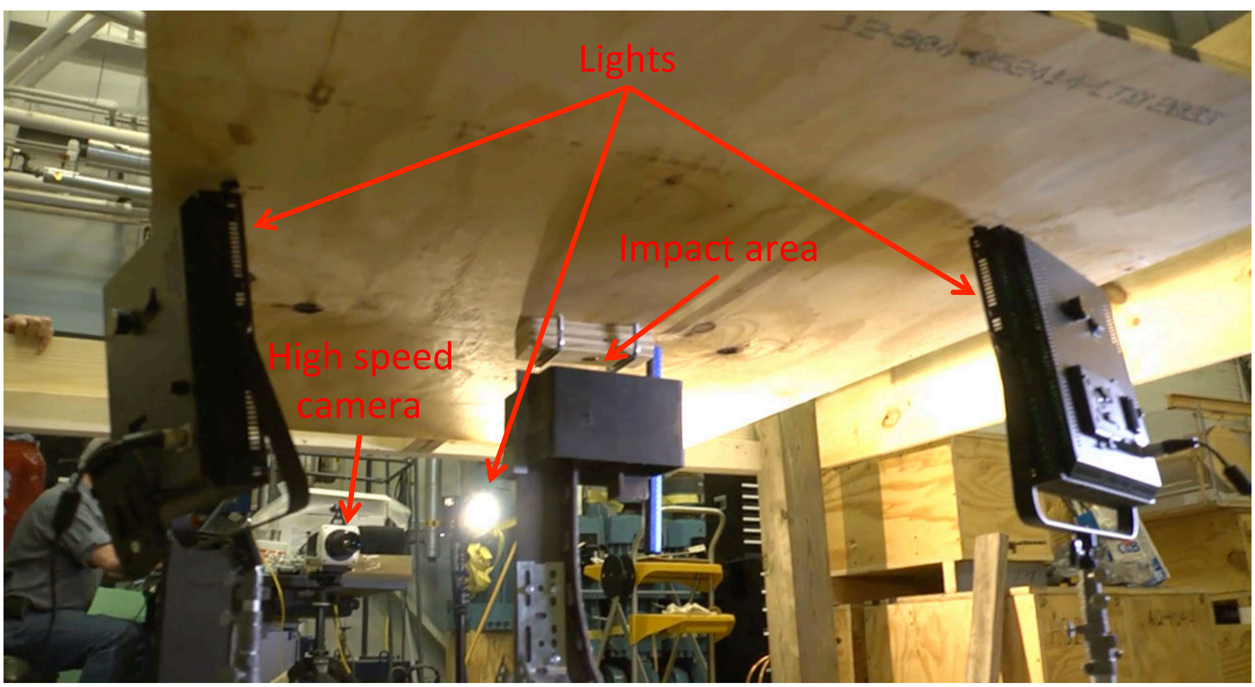


Figure 11. Setup for guided-weight impactor calibration.

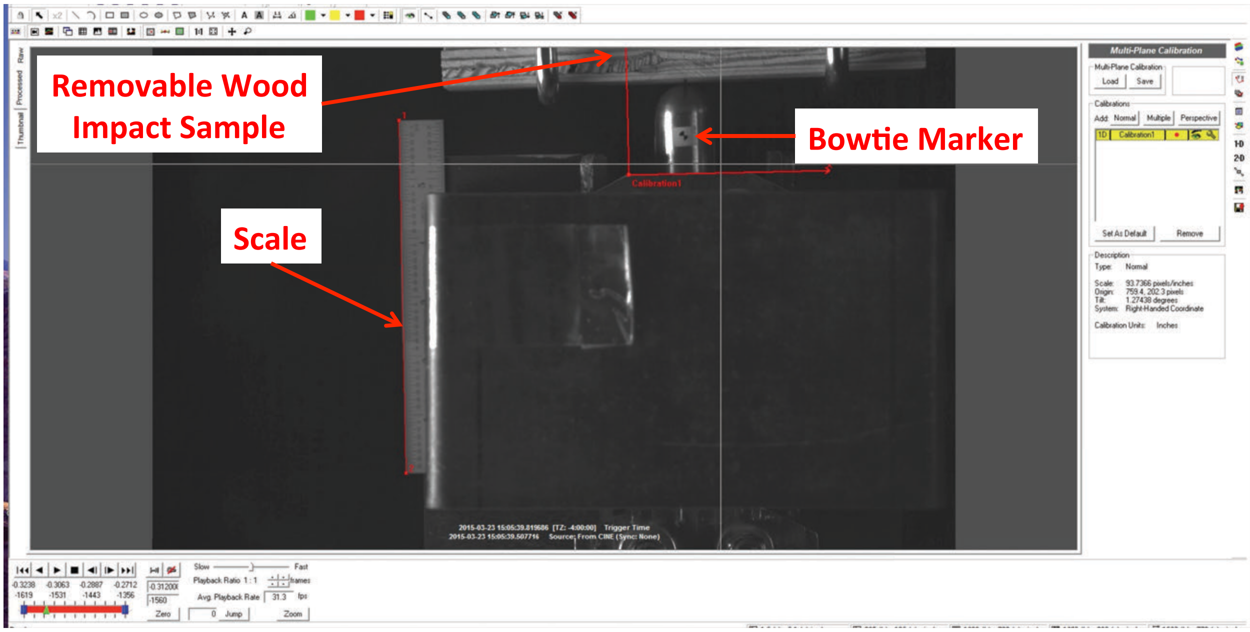


Figure 12. Example velocity measurement screen capture.

Figure 13. Wood impact sample from 5-lb weight impact test.

Exterior Impacts

The impactor was used to impact the MBB while it was installed in the COLTS Facility, as shown in Figure 14 for the skin impact. Alignment of the impactor for applying the exterior skin impact is shown in Figure 15. Alignment was performed by locating the track with the weight held in position in near contact with the surface so that the nose of the tup could be matched up with a cross mark that indicated the desired location of the impact. It is possible to replace the tup with a part that holds a laser that would point at the surface to make alignment even more accurate, but that extra effort was not employed for the MBB. The impactor was leveled using a level on the track base, and the position was achieved using the leveling pads built into the wheels. In Figure 15, weights can be seen on the floor at the capture end of the impactor. These weights were placed tight against the end of the impactor while the impact was being imparted to provide reactive support in order to prevent the impactor from moving when the weight was making the tight turn prior to impact. The weights were necessary because during the calibration tests, it was found that the friction on the six rubber supports was not sufficient to prevent movement of the track during impacts.

The skin impact on the center keel, impact (E3), is shown in Figure 16, where the dent depth was 0.085-inches deep and approximately 0.79 inches in diameter. The impact was within about a sixteenth of an inch of the desired location, and the impact velocity was 14.17 ft/s compared to the target of 13.89 ft/s, for error of about 2.02%. The combination of the dent development and the structural deflection resulted in the tup traveling a distance of approximately 15/32 of an inch (0.469 inches) after initial tup contact. Superimposed images at impact and maximum deflection are shown in Figure 17. Also shown in the figure is the total deflection as indicated by a red line superimposed upon the scale at the right-hand side of the image. Therefore, the structure had an elastic deformation of approximately 0.384 inches as a result of the 15 ft-lb impact on the skin.

The stringer flange impact (E2) is shown in Figure 18, where the dent depth was 0.088-inches deep and approximately 0.62 inches in diameter. The impact was within about a sixteenth of an inch of the desired location, and the impact velocity was 14.61 ft/s compared to the target of 14.65 ft/s, for an error of -0.27%. The combination of the dent development and the structural deflection resulted in the tup traveling a distance of approximately 11/32 of an inch (0.344 inches) after initial tup contact. Superimposed images at impact and maximum deflection are shown in Figure 19. Also shown in the figure is the total deflection as indicated by a red line superimposed upon the scale at the right-hand side of the image. Therefore, the structure had an elastic deformation of approximately 0.256 inches as a result of the 15 ft-lb impact on the skin.

The frame flange impact (E1) is shown in Figure 20. Unfortunately, the impact weight tup fully penetrated the test article, with the wheel brackets coming to rest against the surface of the test article as shown in Figure 21. During this penetration process the impact weight shifted, as shown in Figure 22. This shift resulted from a combination of shift in the entire track due to the resulting force on the tup while penetration was occurring, and shift of the impact weight once the forward wheels of the weight exited the end of the track and were no longer constrained. In Figure 22, it is seen that each of these shifts is equal, approximately 3/32 of an inch, as shown by the yellow and orange lines superimposed on the scale at the right-hand side of the image. The total shift resulting from these shift component values is 3/16 of an inch, depicted by the red line superimposed on the scale in the image of Figure 22. Accounting for this shift, the approximate initial impact location is indicated in Figure 23 by the yellow cross. This initial impact location was within a sixteenth of an inch of the desired location, and the impact velocity was 15.75 ft/s compared to the target of 16.04 ft/s, for an error of about -1.81%. Several factors were potential contributors to the penetration at the frame flange impact location (E1). First, the blue target mark shown in Figure 20 was not at the desired location, and is farther from the stitch line than that for the stringer flange impact (E2) in Figure 18. Additionally, it appears that, by comparing the interior images in Figure 18 for E2 and Figure 20 for E1, there is more substantial flange on the skin side of the stringer flange stitch line, which provided additional material to absorb the impact at the E2 location. The shift of the entire track was the result of the weights and sand bags being insufficient to keep the track from moving during the impact due to the bearing force that was being applied to the tup. Additional track restraint (weight or other means) might have prevented track movement and may have lessened the penetration of the tup. Lastly, due to the combination of tup penetration and elastic deformation of the test article, the wheels of the impact weight became disengaged from the track, which permitted additional shift in tup location as the tup was bearing at the flange stitch line. If the track end was closer to the test article, then this additional shift and resulting penetration may have been lessened. The resulting damage was much more severe than BVID, but testing demonstrated that this severe damage did not result in any growth.[11]

The exterior impacts were carried out with good precision, within about a sixteenth of the target locations, and within good agreement of the required velocity values (and therefore impact energies). In fact, the exterior impacts using the guided drop weight impactor were within about 2% of the required energy values, whereas the interior impacts imparted using the compressed spring impactor were in error up to about 8.5%.[17] This accuracy in energy level is attributable to the repeatability of the gravity-driven system resulting from the ability to accurately locate the weight at the proper starting location with tight tolerance. Table 4 summarizes the target velocities, actual velocities, and errors for the three exterior impacts.

Table 4. Summary of MBB exterior impact velocities, ft/s, and percent errors.

ID	Description	Target Velocity	Actual Velocity	Error (%)
E1	Keel, Frame Flange	16.04	15.75	-1.81
E2	Keel, Stringer Flange	14.65	14.61	-0.27
E3	Keel, Center Skin Bay	13.89	14.17	2.02

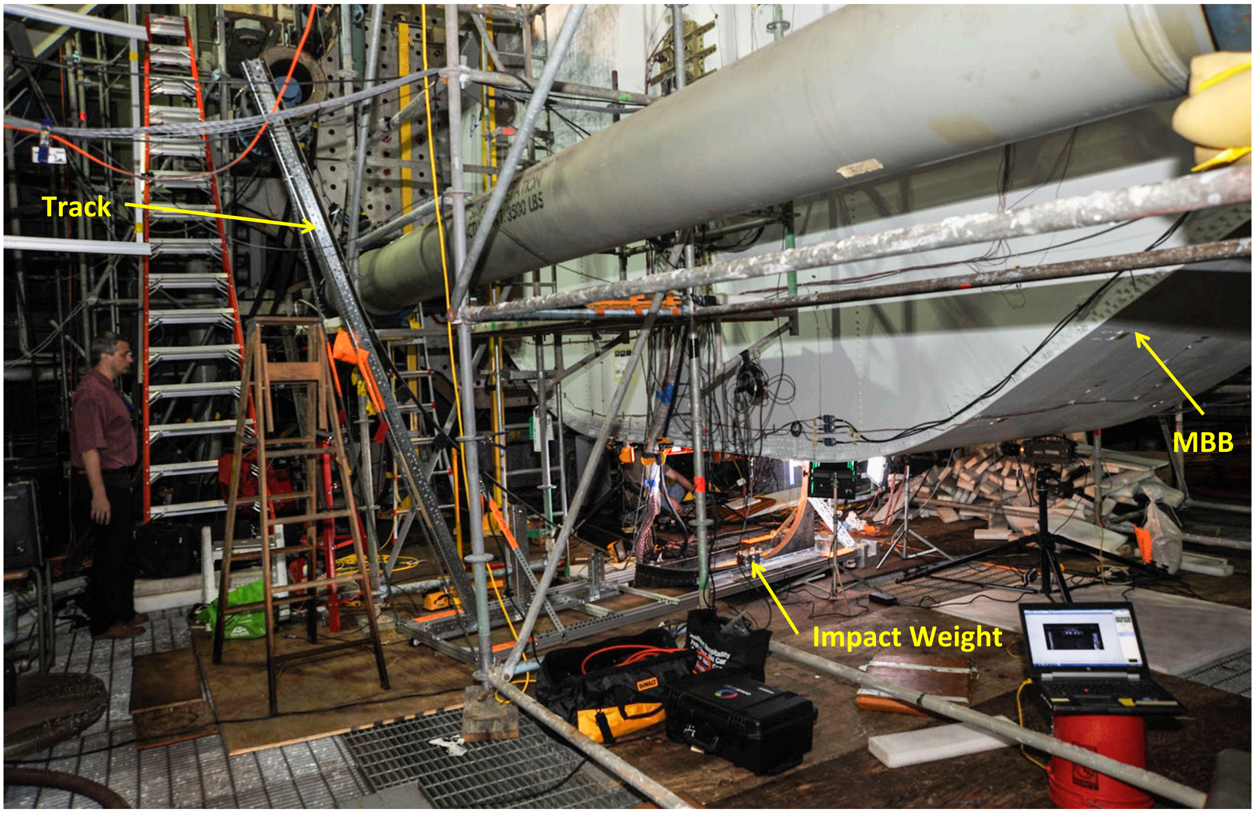
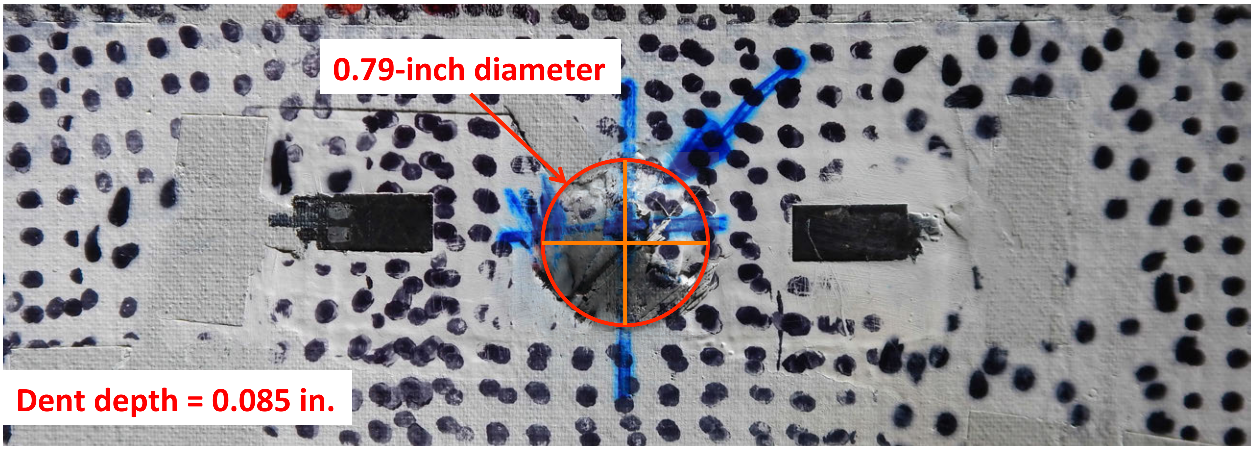


Figure 14. Impactor in COLTS in location to impart exterior skin BVID to MBB keel.

Figure 15. Alignment of impactor for exterior skin impact.



a) Exterior surface, where the blue and orange crosses indicate the target and actual impact locations, respectively

b) Interior surface

Figure 16. Center keel after exterior skin impact.

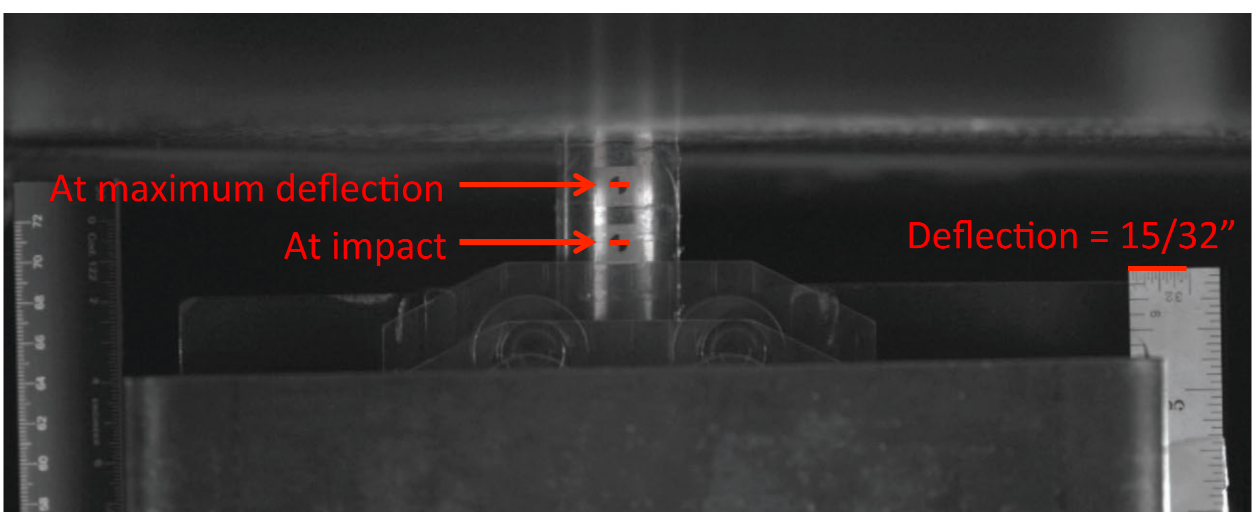
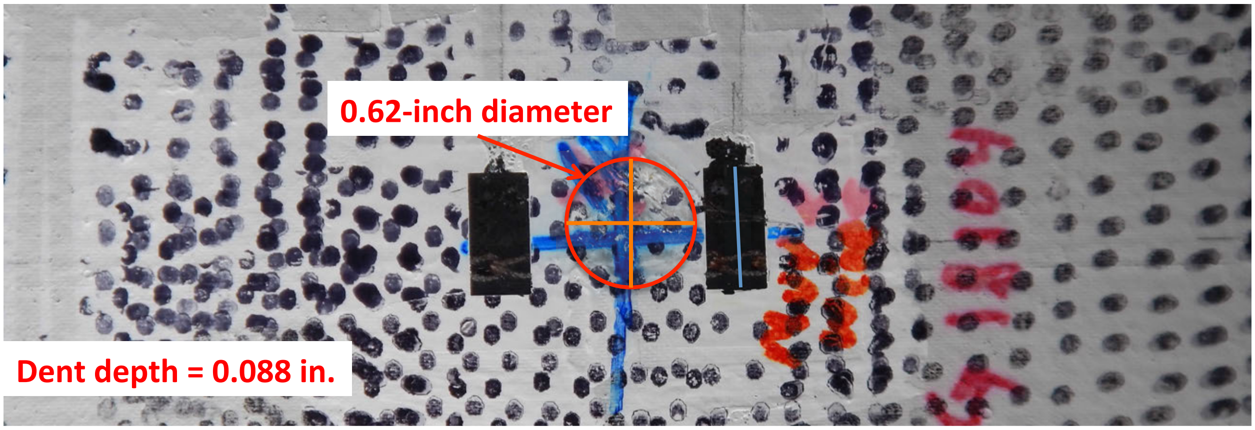
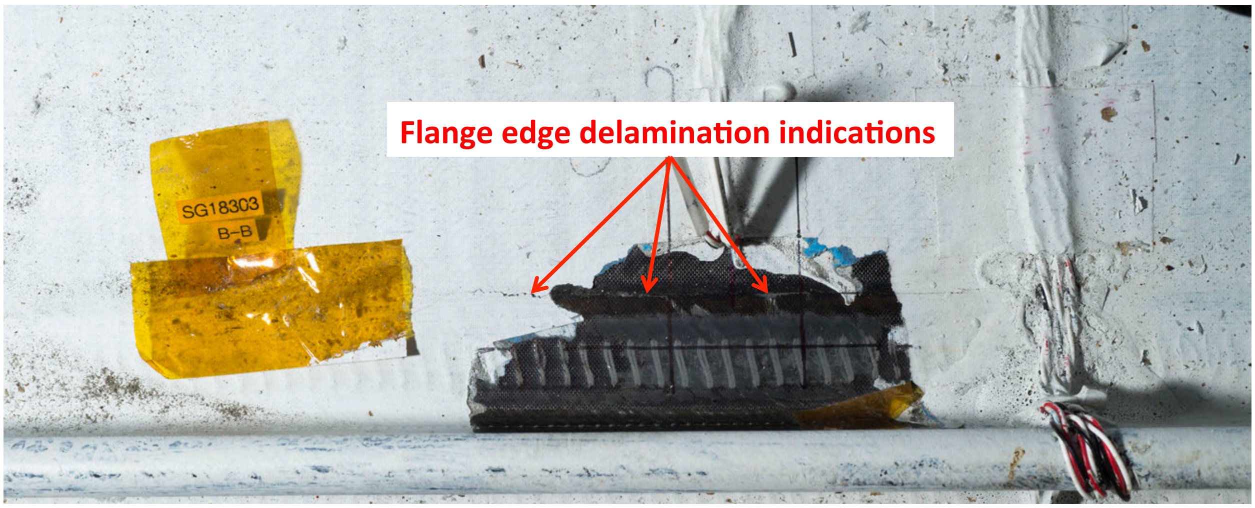


Figure 17. Position of impact tup during exterior skin impact.



a) Exterior surface, where the blue and orange crosses indicate the target and actual impact locations, respectively



b) Interior surface

Figure 18. Center keel after exterior stringer flange impact.

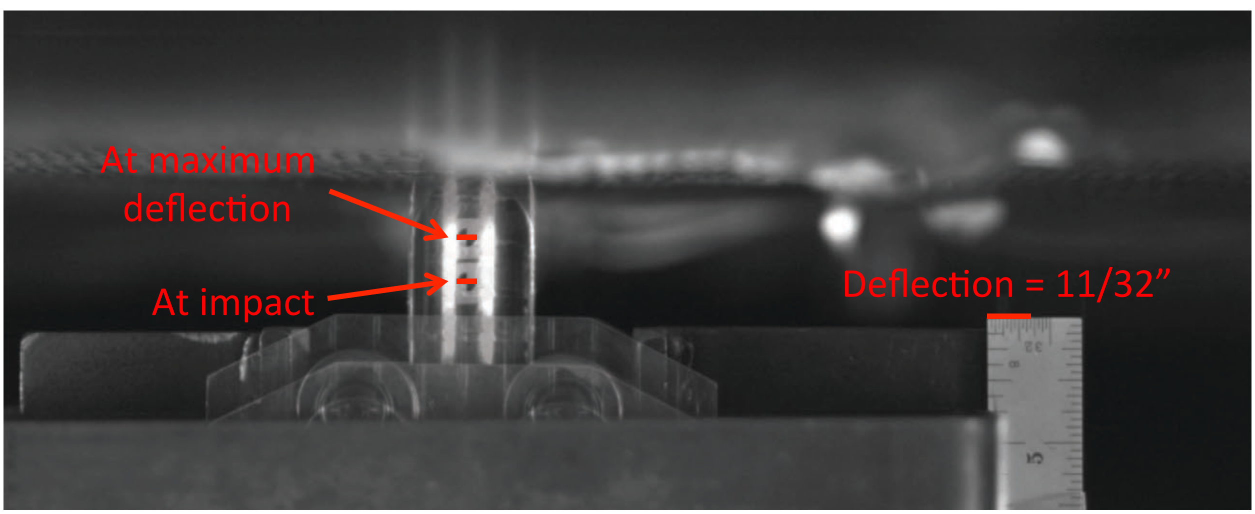
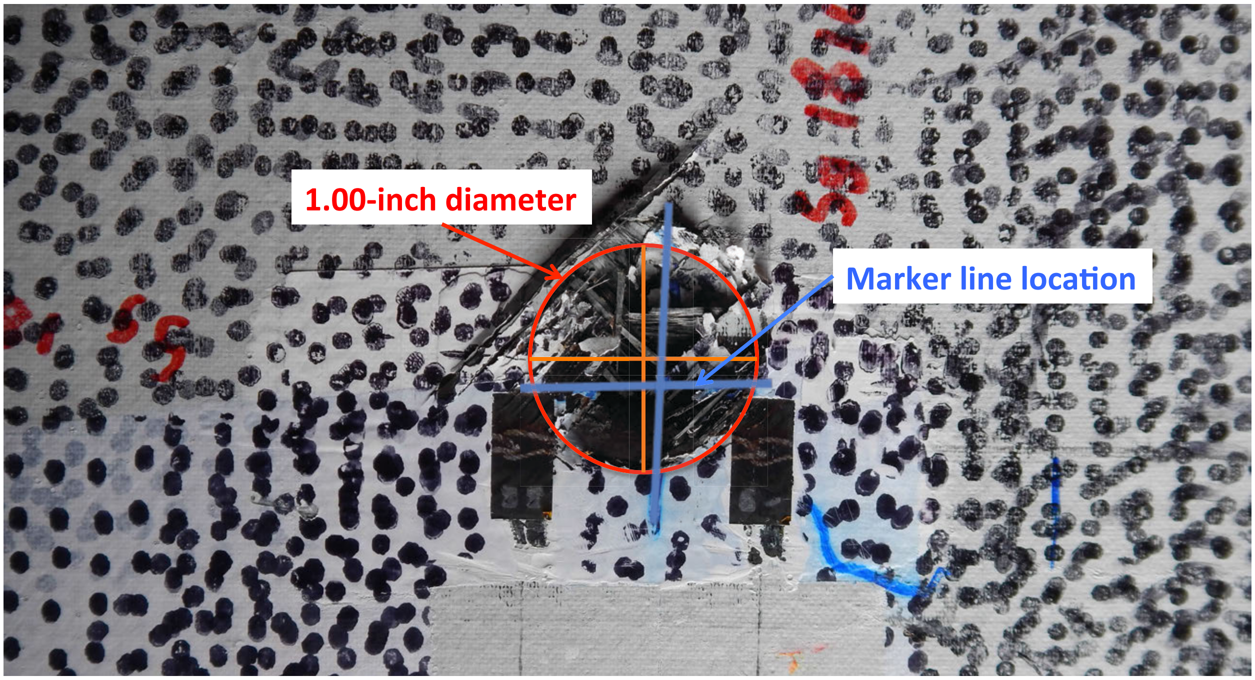
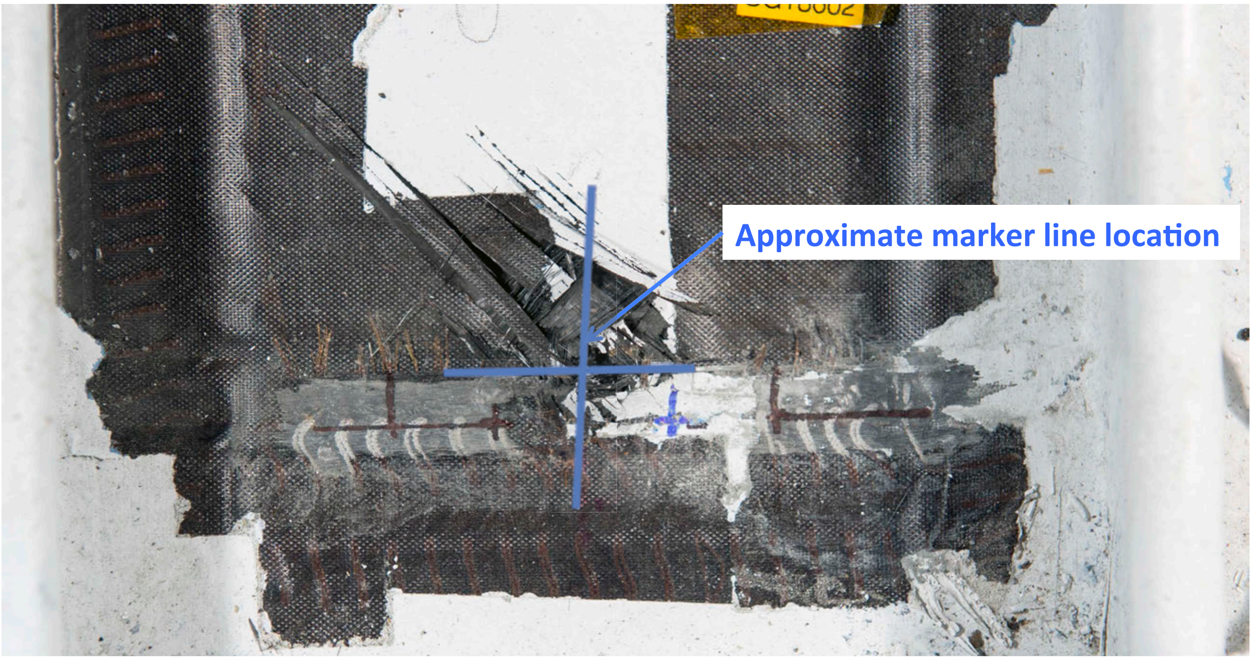


Figure 19. Position of impact tup during exterior stringer flange impact.

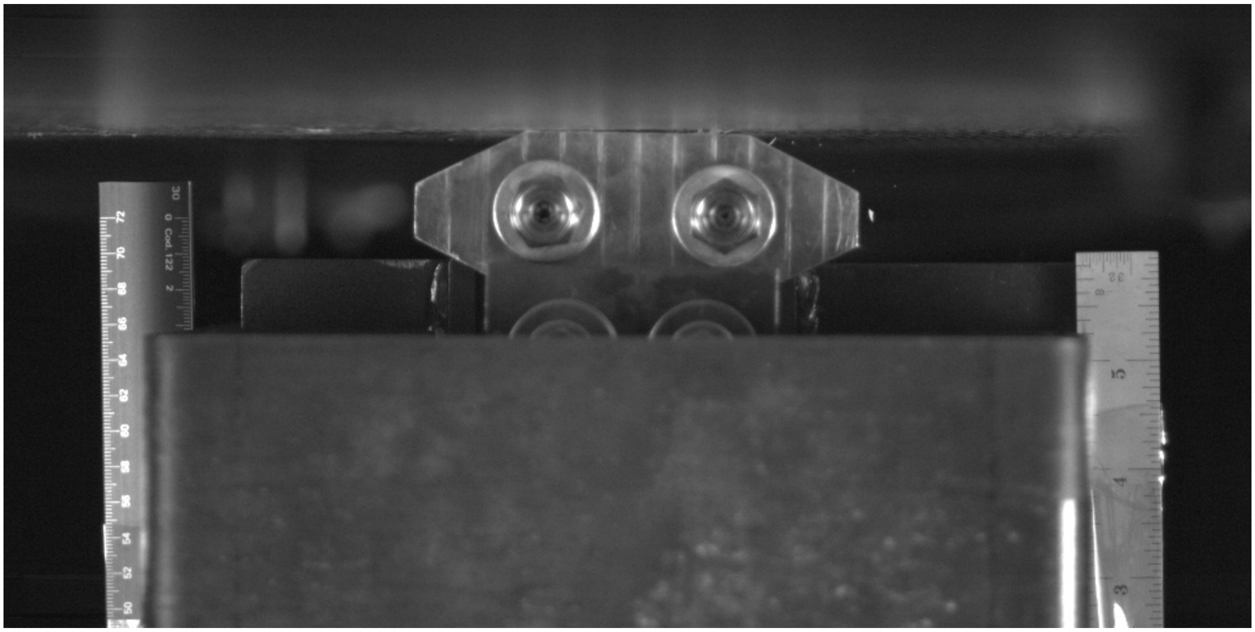


a) Exterior surface, where the blue and orange crosses indicate the target and actual impact locations, respectively



b) Interior surface

Figure 20. Center keel after exterior frame flange impact.



a) Exterior

b) Interior

Figure 21. Impact tup penetrating MBB after exterior frame flange impact.

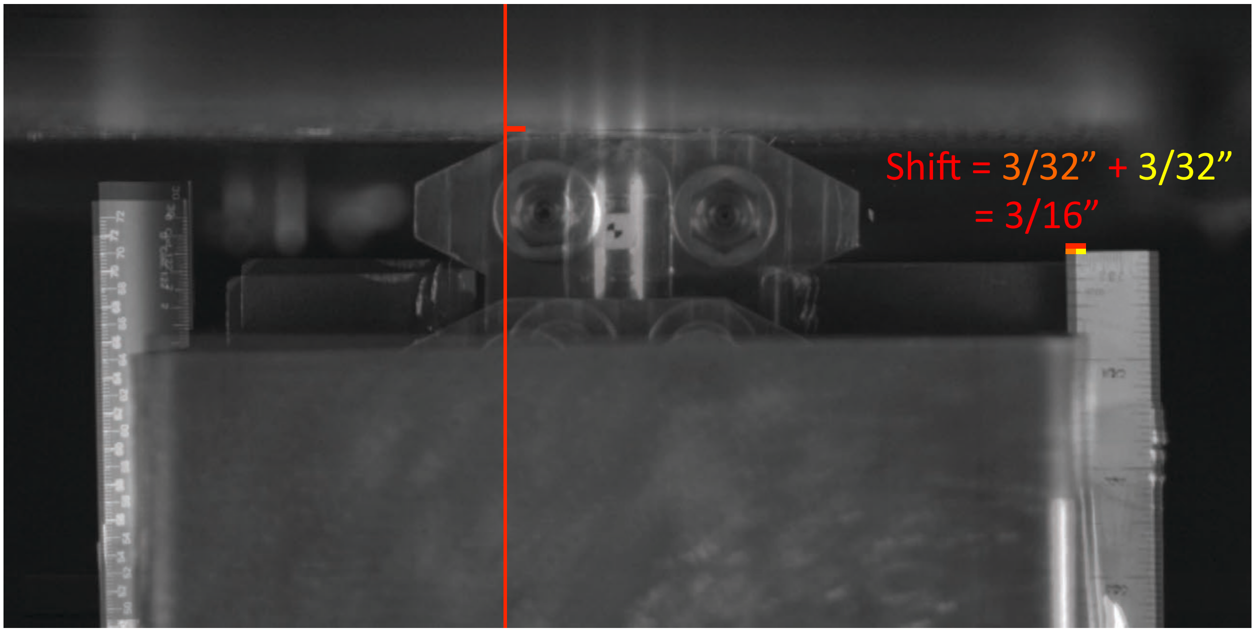


Figure 22. Position shift during exterior frame flange impact.

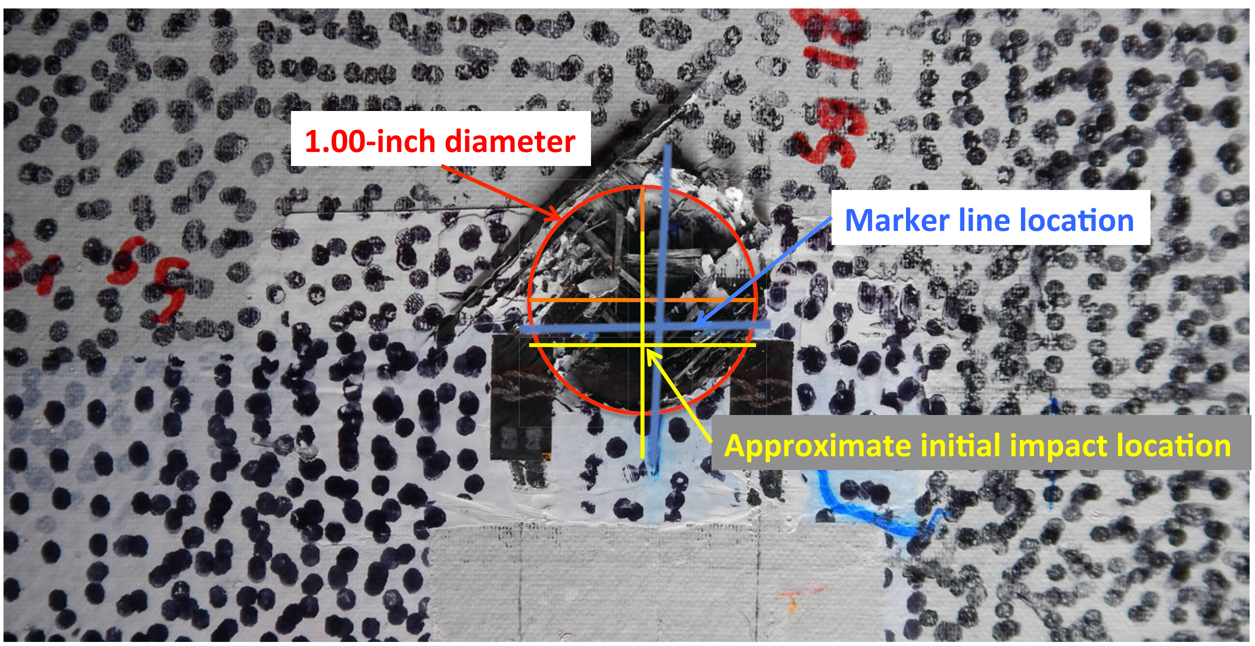


Figure 23. Initial position of impact tup during exterior stringer flange impact.

Concluding Remarks

Impacts to generate BVID on the MBB test article were carried out at the NASA LaRC COLTS Facility. Interior impacts were conducted using an existing spring-loaded device, while the exterior impacts were conducted using a newly developed guided drop weight impactor. The guided drop weight impactor used for the exterior impacts was able to achieve repeatable velocities at impact, while at the same time impacting the MBB at the required location within approximately a sixteenth of an inch. The impact velocities (and, therefore, the impact energy) for the three exterior impacts were found to be within 2% of the desired value, compared to the spring-loaded impactor used to impart the interior BVID that had velocity errors up to 8.5%, with the largest error being for the lower velocity.[17] The small error in the gravity-driven impactor emphasizes the accuracy and repeatability of the gravity-driven method. A number of possible sources contributing to the full penetration at the frame flange impact location were discussed, and if they were addressed, such an event can be prevented. However, it was found that the presence of the full penetration had no effect on the response of the MBB to applied loads.[11] Lastly, the newly-developed guided drop weight impactor can be reconfigured in both impact weight and track orientation for use on other large-scale test articles. For impacts to the MBB described herein, only the weight was reconfigured.

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[19]www.visionresearch.com, March 25, 2015.

Appendix A: Impact Weight Drawings

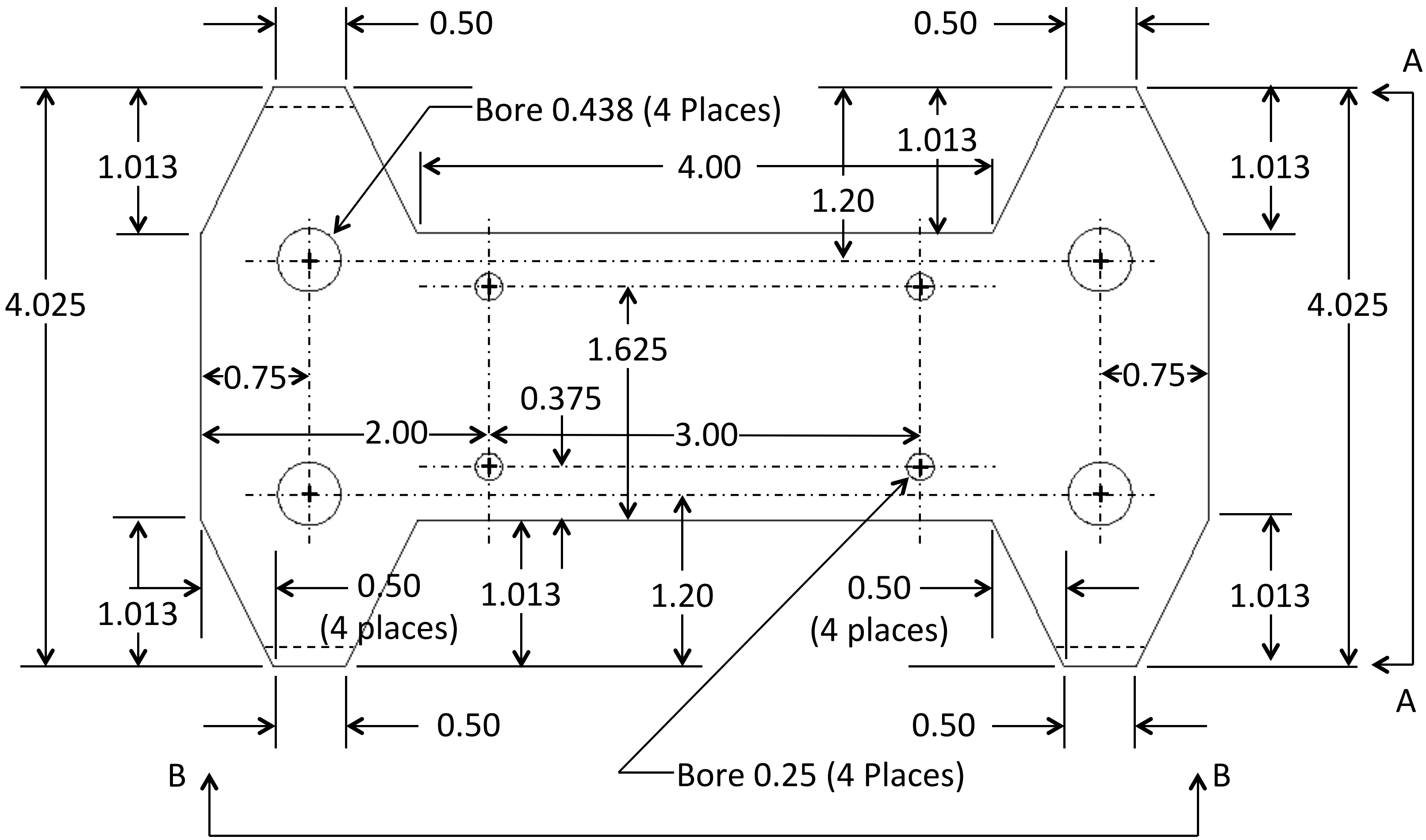
This appendix provides the drawings used to fabricate the components used in the impact weights. Details of which drawings apply to the 5-lb and 15-lb variants of the impact weights are provided in the Guided-Weight Impactor Design section. Drawings are only for the portions of the weights that were fabricated, with purchased components provided in the aforementioned section. These weights are appropriate for use on any impact that requires 5-lb or 15-lb impact weights, and the baseline 5-lb model is capable of being configured with other added weight components to accommodate other impact weight requirements.

Drawing #RCI0007 – Sheet 1 (rev. 2)

Part: Car Wheel Bracket

Lovejoy, A.

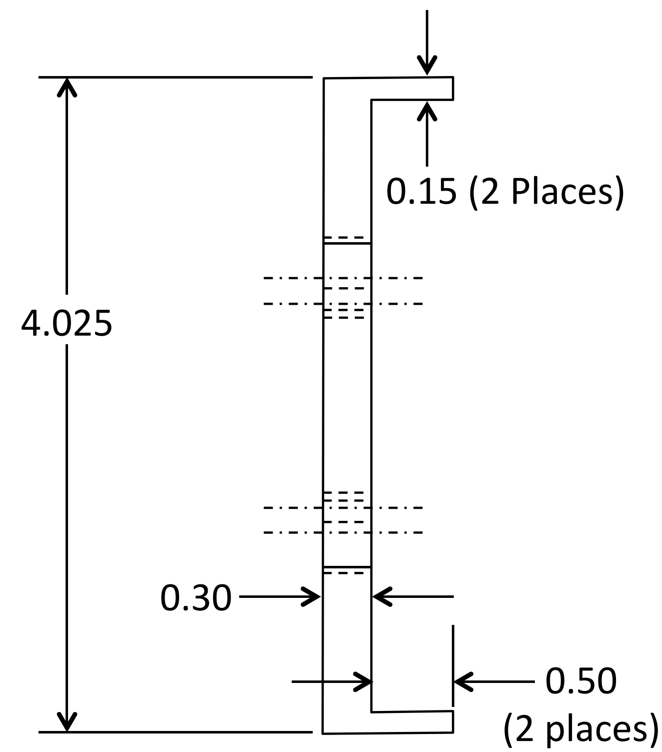
Notes:
1) Fabricated from aluminum plate stock.
2) Bore tolerance +0.005, -0.000.
3) Fabricate 2 pieces.



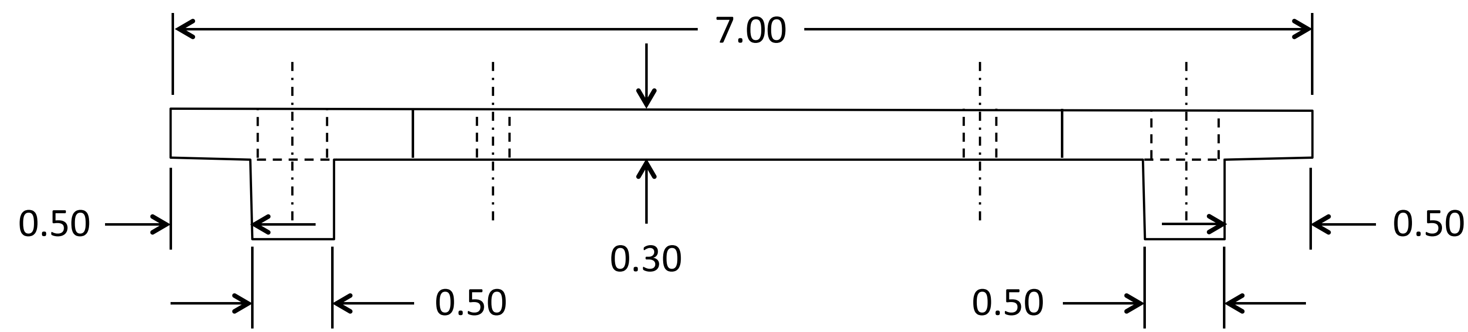
Drawing #RCI0007 – Sheet 2 (rev. 2)

Part: Car Wheel Bracket

Lovejoy, A.



Section A-A



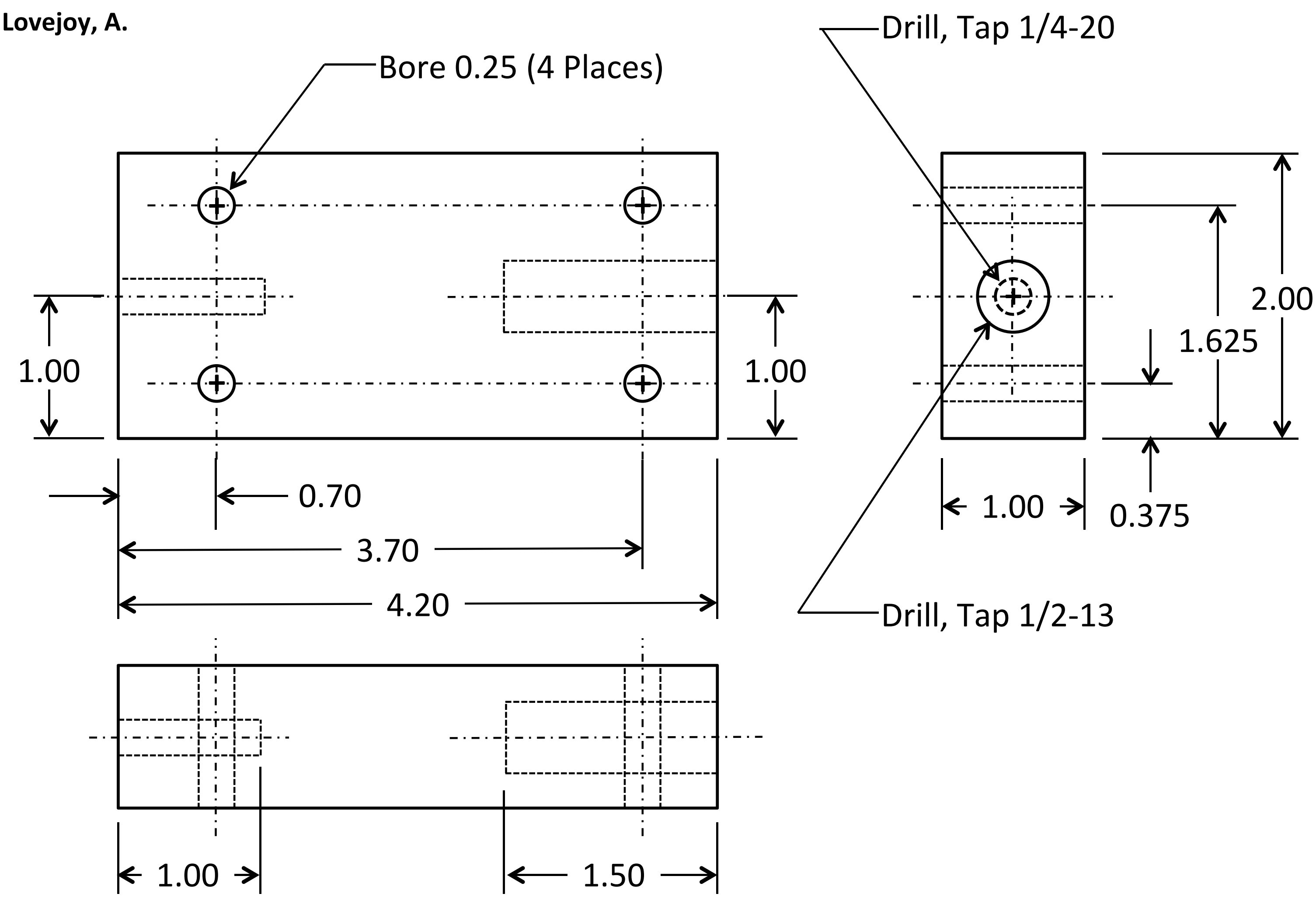
Section B-B

Drawing #RCI0008 – (rev. 1)

Part: Central Block

Lovejoy, A.

Notes:
1) Fabricated from aluminum plate stock.
2) Bore tolerance +0.005, -0.000.

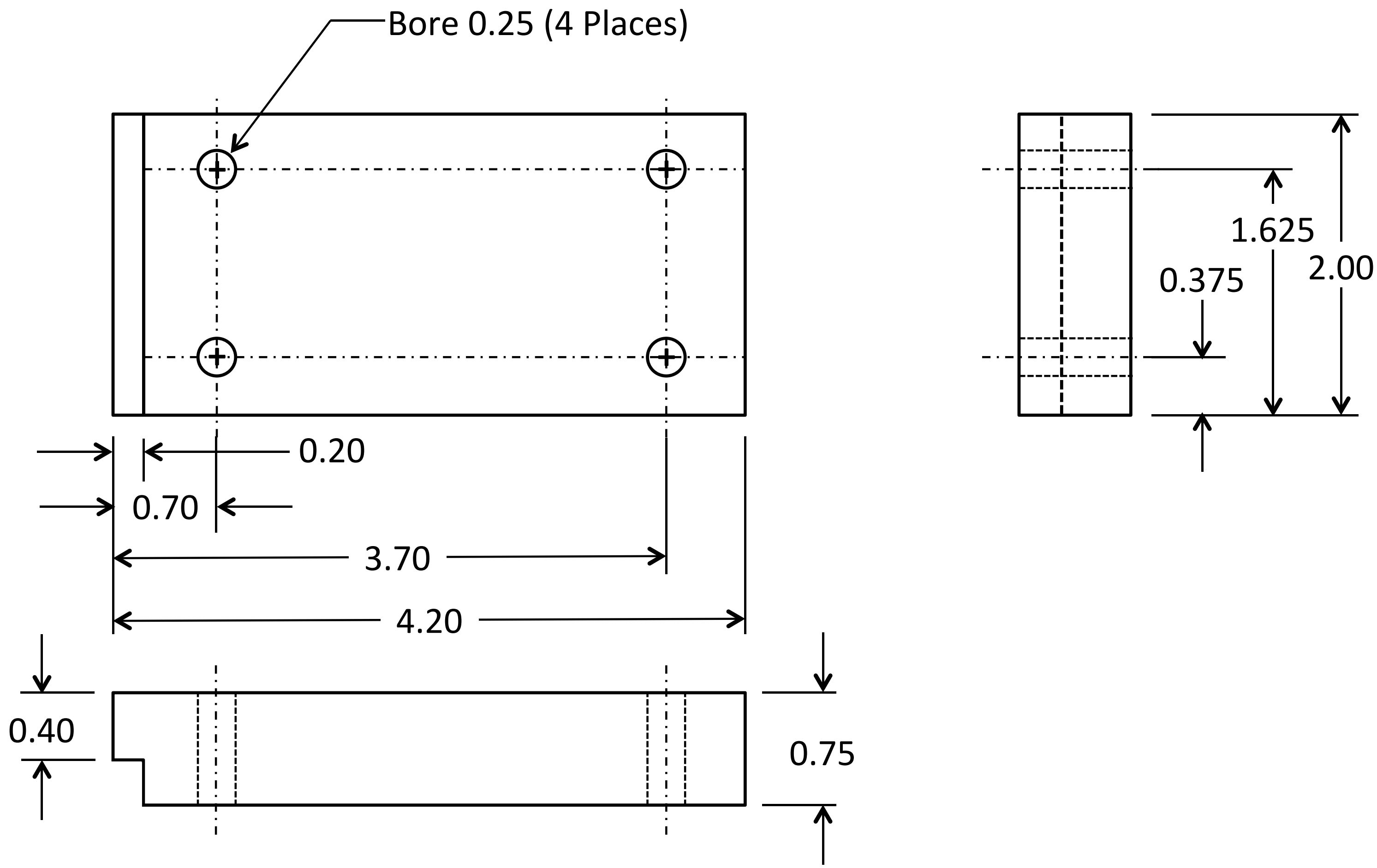


Drawing #RCI0009 – (rev. 1)

Part: Weight Block #1

Lovejoy, A.

Notes:
1) Fabricated from steel plate stock.
2) Bore tolerance +0.005, -0.000.
3) Fabricate 2 pieces.

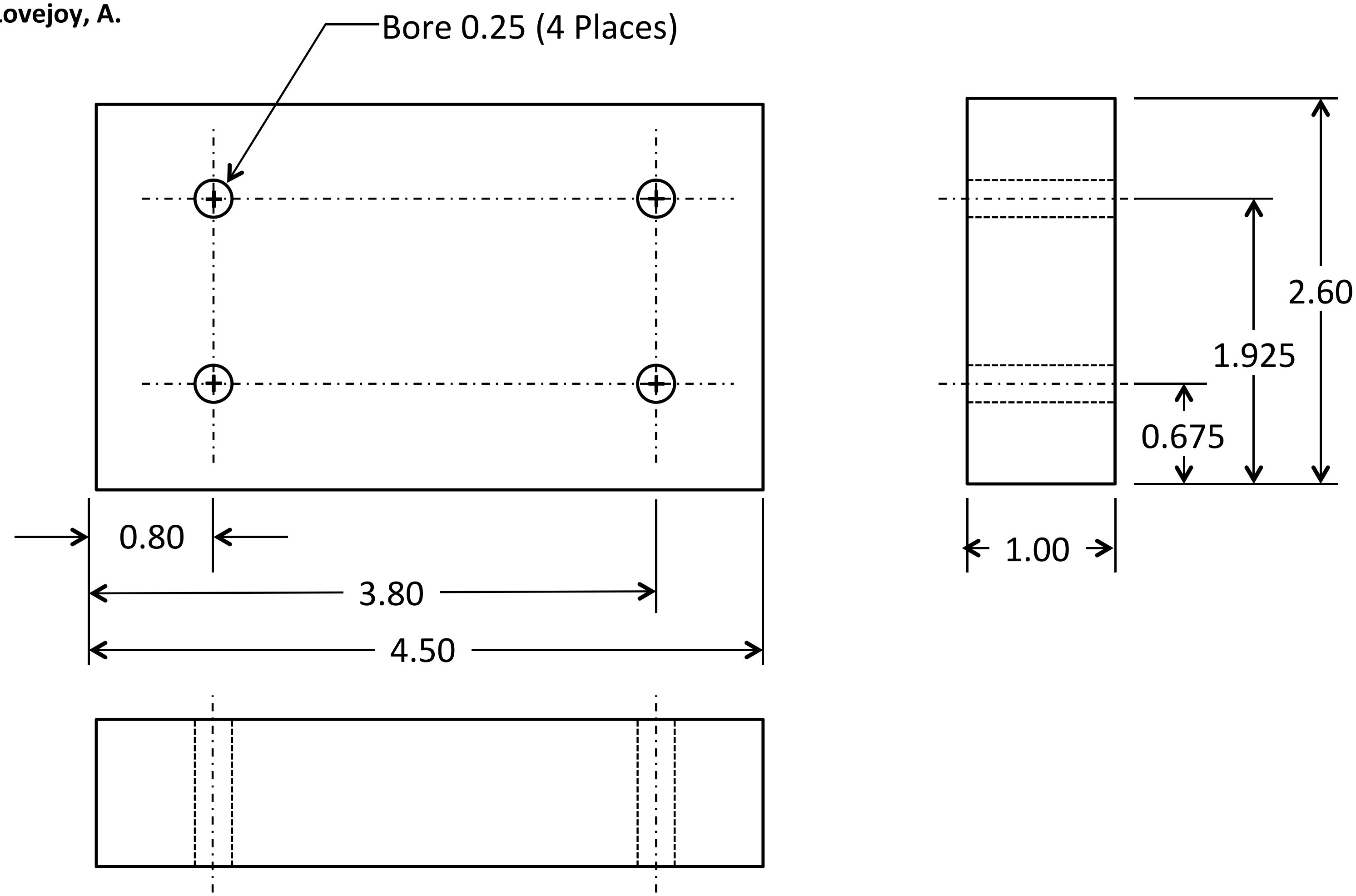


Drawing #RCI0010 – (rev. 1)

Part: Weight Block #2

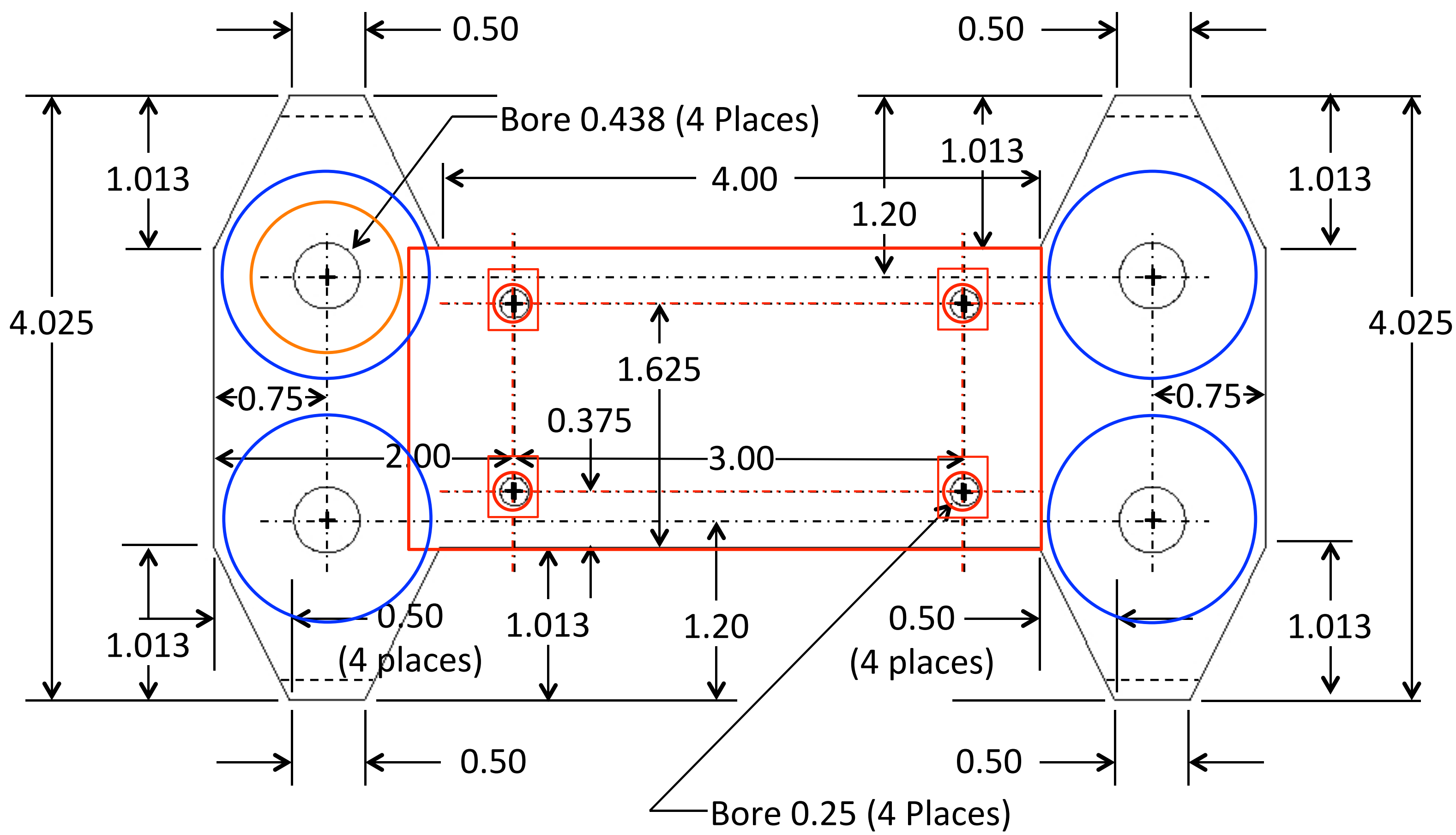
Lovejoy, A.

Notes:
1) Fabricated from steel plate stock.
2) Bore tolerance +0.005, -0.000.
3) Fabricate 2 pieces.



Car Assembly Arrangement

Lovejoy, A.



Appendix B: MBB Impact Track Drawings

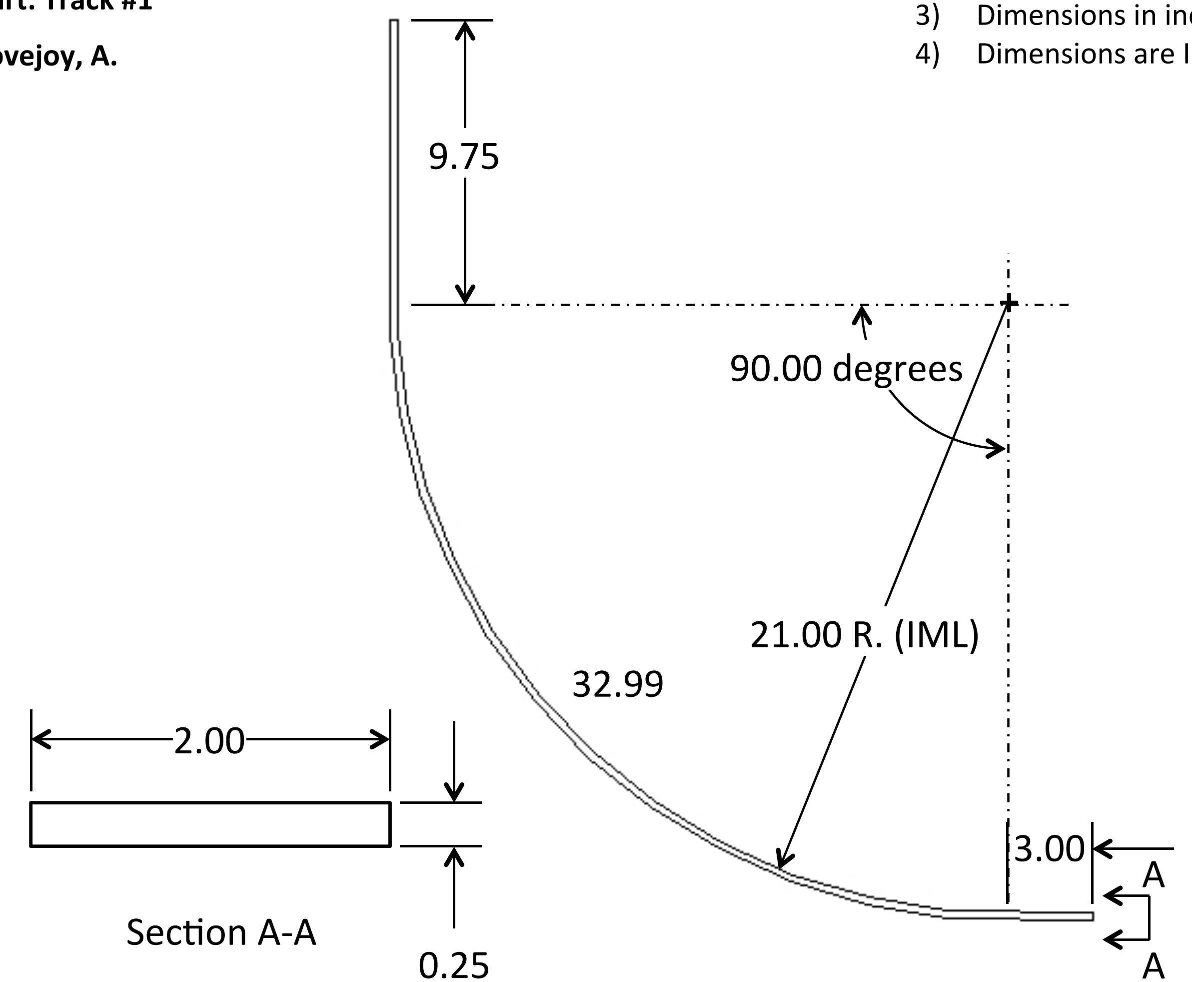
This appendix provides the drawings used to fabricate the components used in the impact track use on the MBB. Details of the track are provided in the Guided-Weight Impactor Design section. Drawings are only for the portions of the track that were fabricated, with purchased components provided in the aforementioned section. This track is specific to the MBB, and would require reconfiguring to be used for impacts at other angles, or for vertical impacts where the distance from the ground to the impact surface is different than that of the MBB.

Drawing #RCI0001 (rev. 1)

Part: Track #1

Lovejoy, A.

Notes:
1) Fabricated from steel bar stock.
2) Both end regions straight.
3) Dimensions in inches.
4) Dimensions are IML for track length.



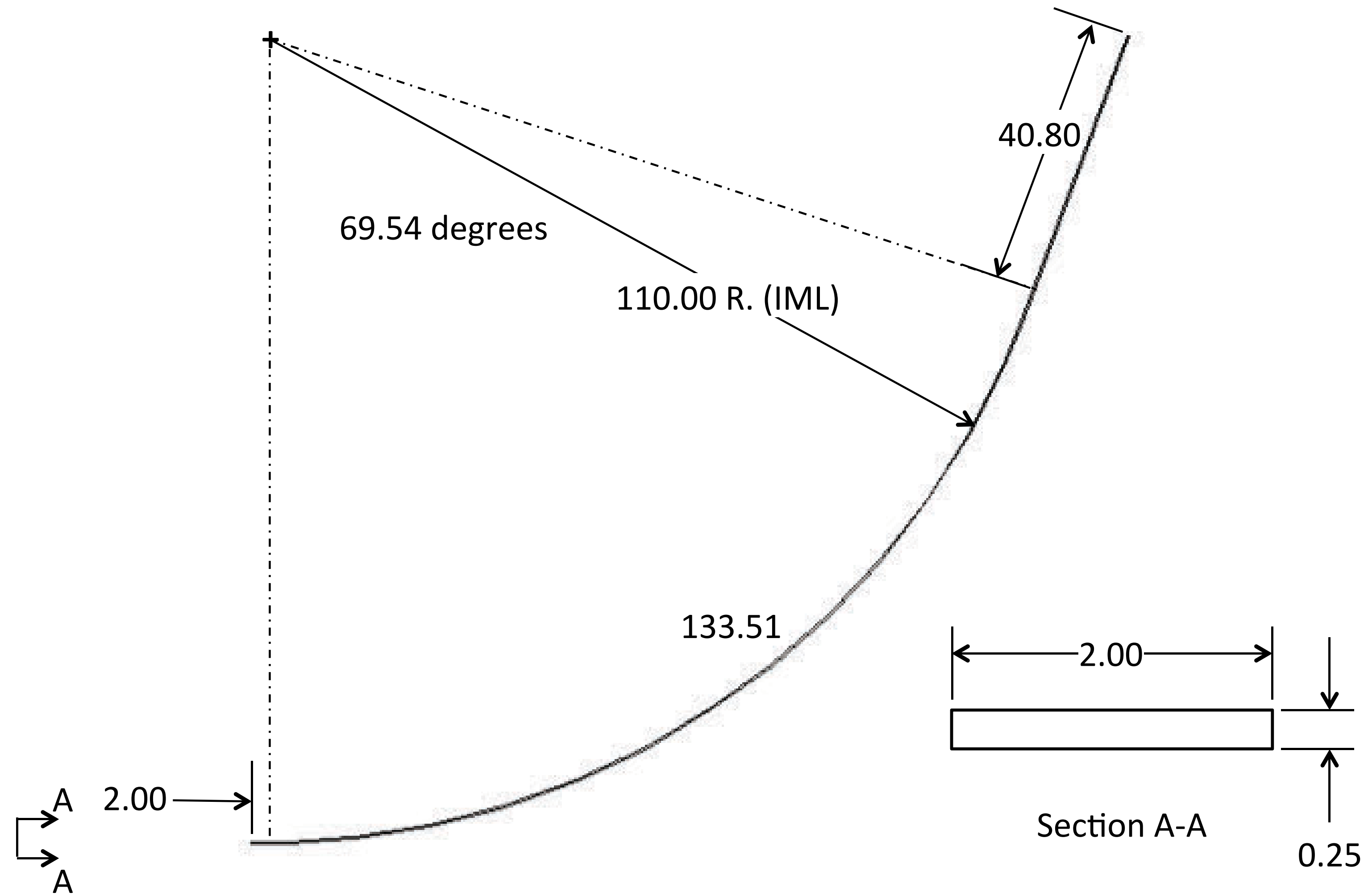
Drawing #RCI0002 (rev. 1)

Part: Track #2

Lovejoy, A.

Notes:

1) Fabricated from steel bar stock.
2) Two end regions straight.
3) Dimensions in inches.
4) Dimensions are IML for track length.

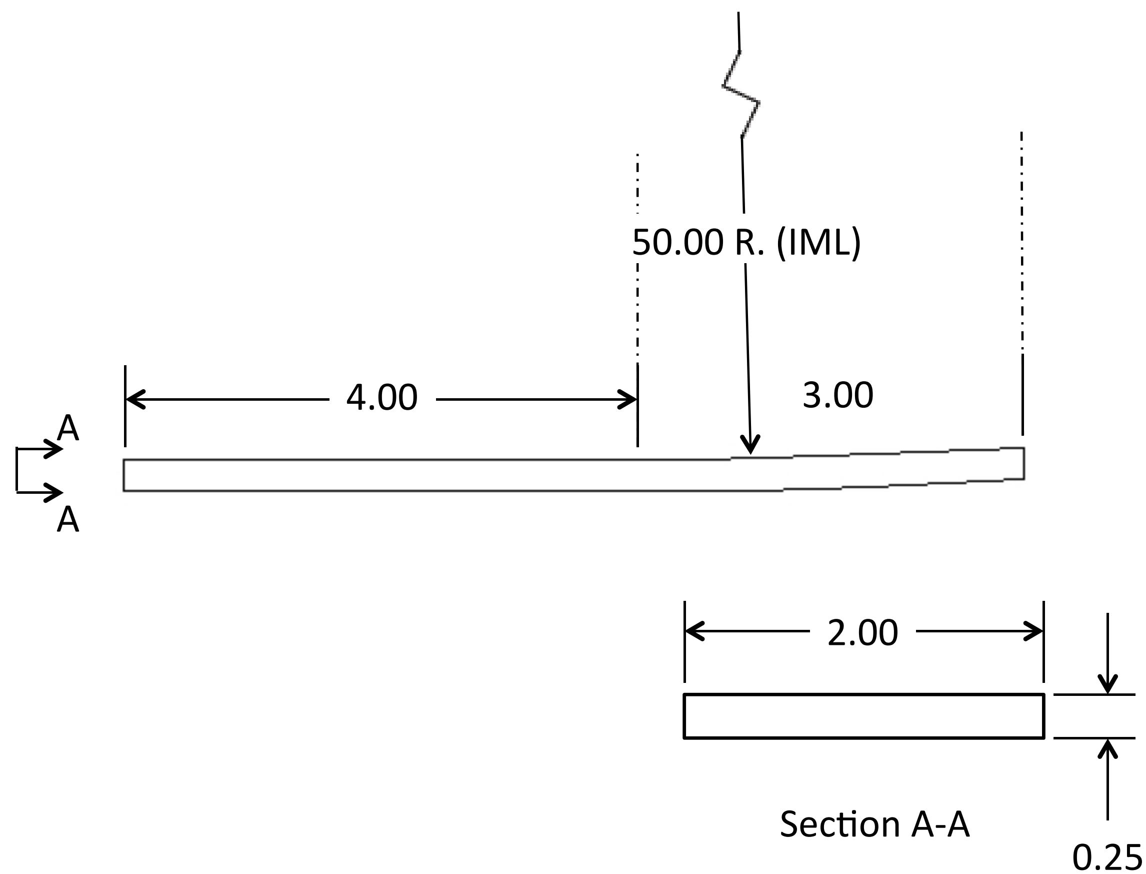


Drawing #RCI0003 (rev. 1)

Part: Track #3

Lovejoy, A.

Notes:
1) Fabricated from steel bar stock.
2) End region straight.
3) Dimensions in inches.
4) Dimensions are IML for track length.

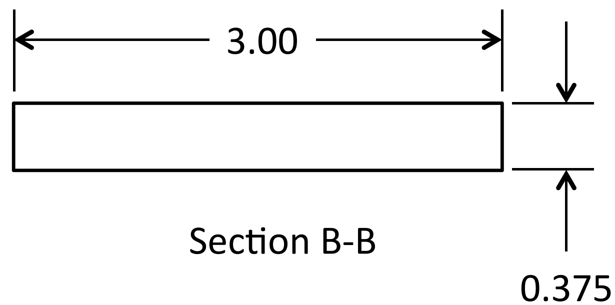


Drawing #RCI0004 (rev. 1)

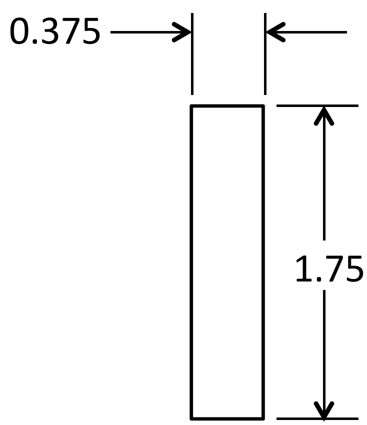
Part: Track #1 Web

Lovejoy, A.

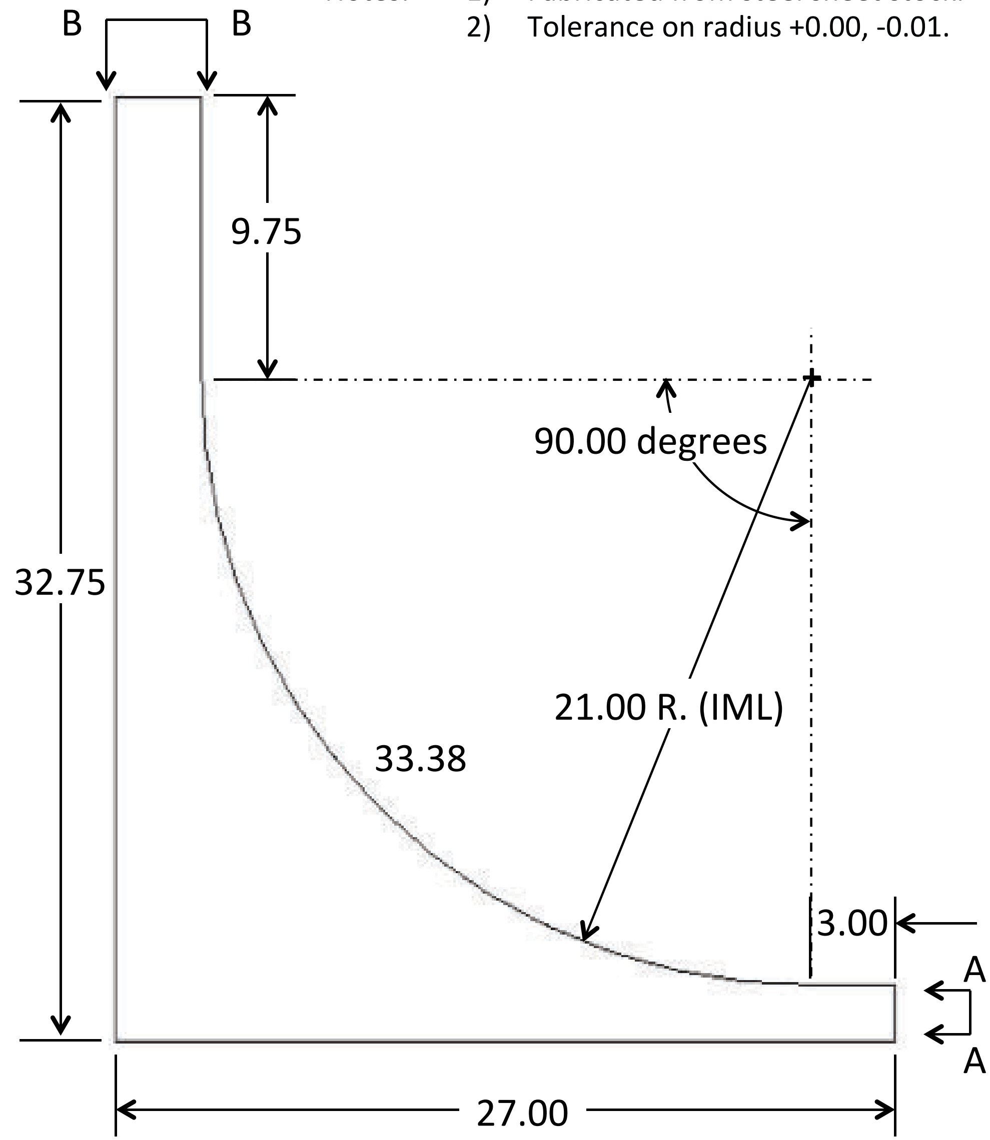
Notes:
1) Fabricated from steel sheet stock.
2) Tolerance on radius +0.00, -0.01.



Section B-B



Section A-A

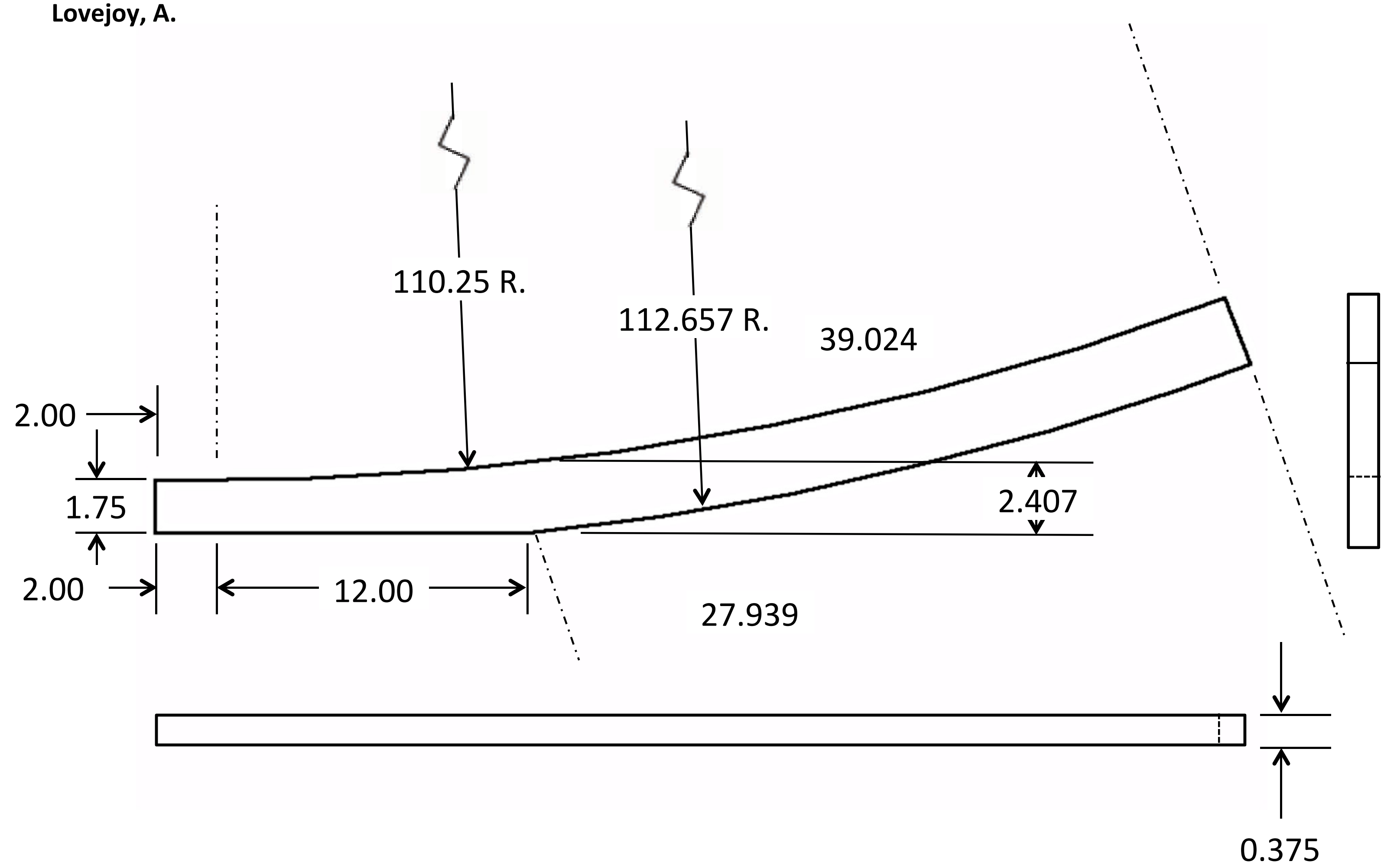


Drawing #RCI0005 (rev. 2)

Part: Track #2 Web

Lovejoy, A.

Notes:
1) Fabricated from steel sheet stock.
2) Tolerance on radius +0.00, -0.01.

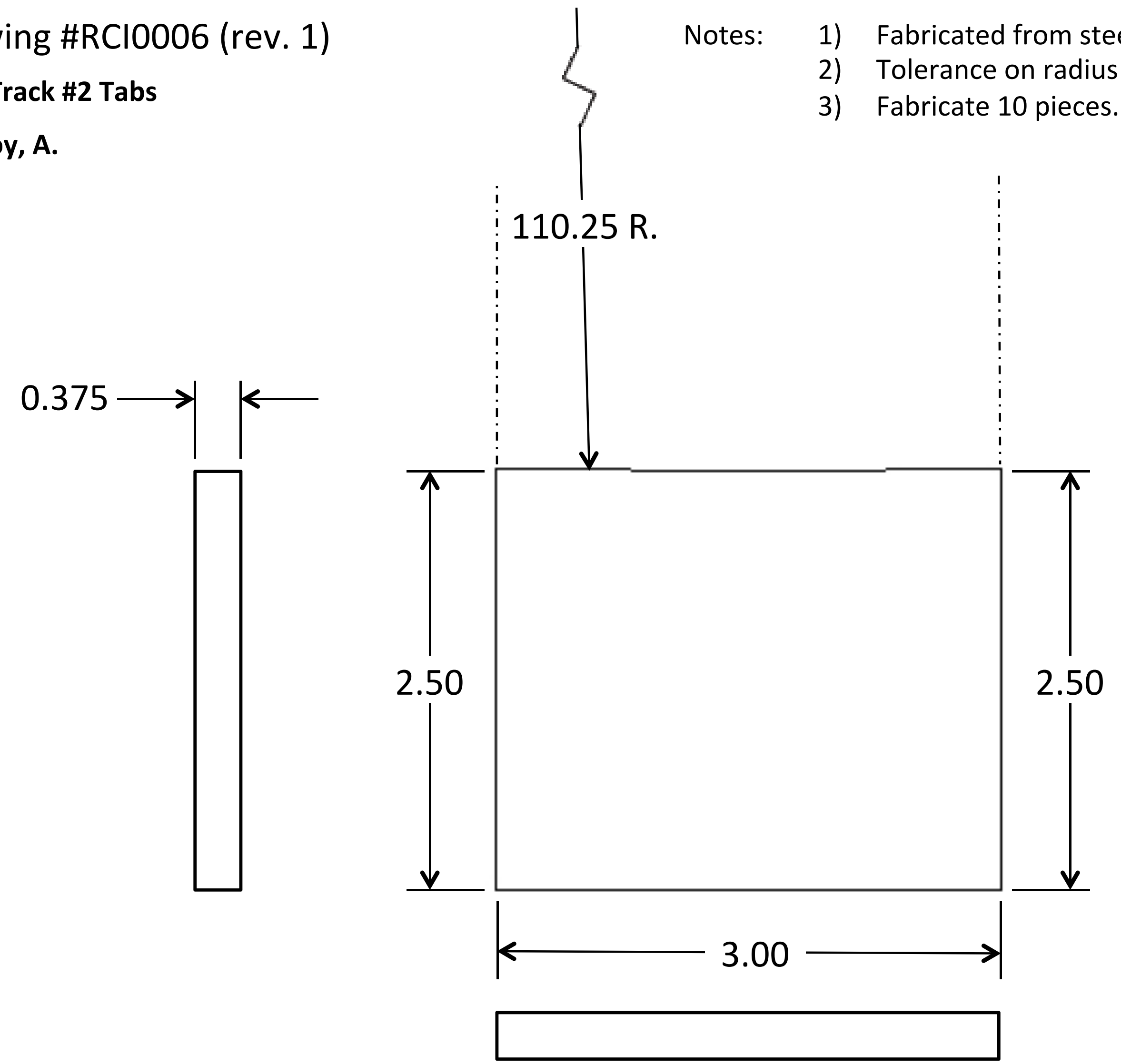


Drawing #RCI0006 (rev. 1)

Part: Track #2 Tabs

Lovejoy, A.

Notes:
1) Fabricated from steel sheet stock.
2) Tolerance on radius +0.00, -0.01.
3) Fabricate 10 pieces.

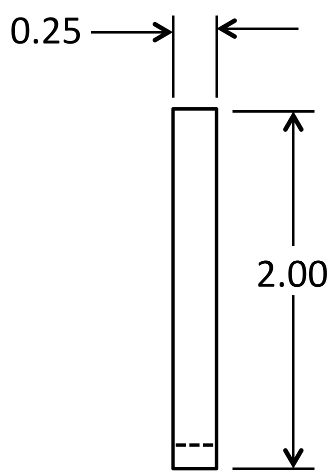


Drawing #RCI0011 (rev. 1)

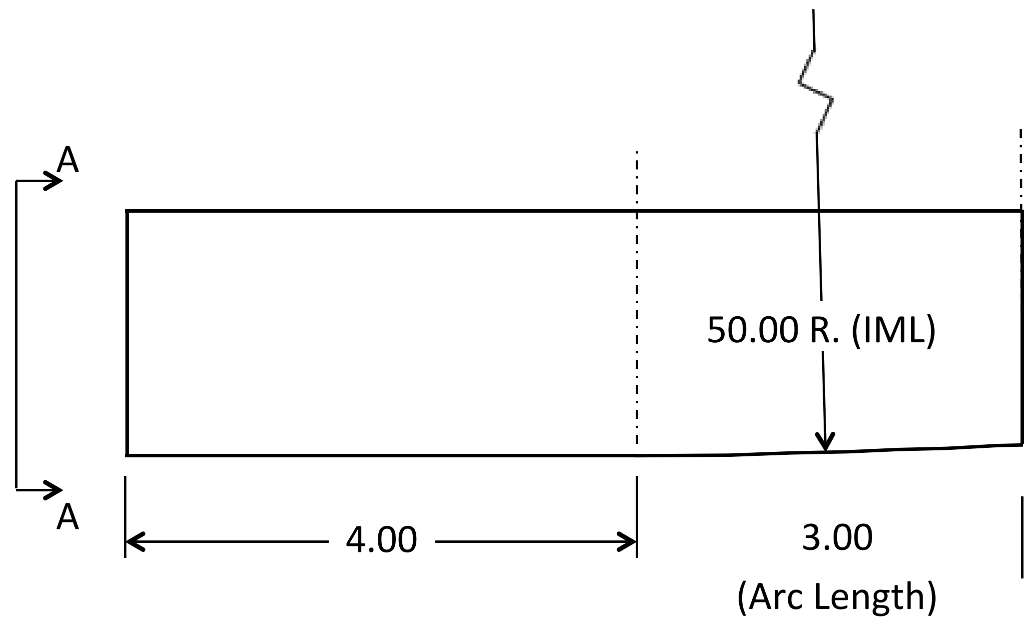
Part: Track #3 Web

Lovejoy, A.

Notes:
1) Fabricated from steel bar stock.
2) End region straight.
3) Dimensions in inches.
4) Length dimensions are OML.



Section A-A



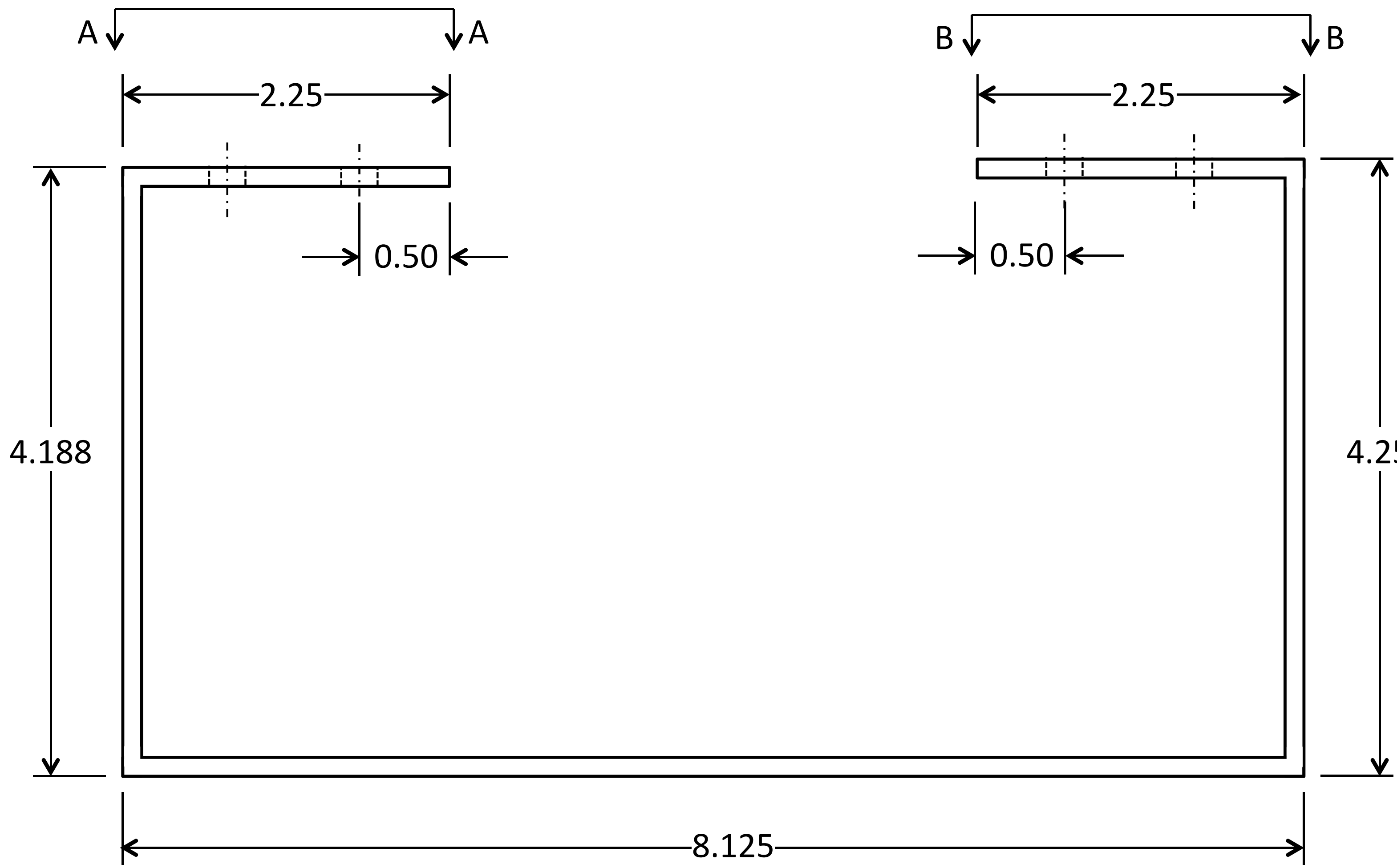
Drawing #RCI0012, Sheet 1 (rev. 1)

Part: Track #3 Brace

Lovejoy, A.

Notes:

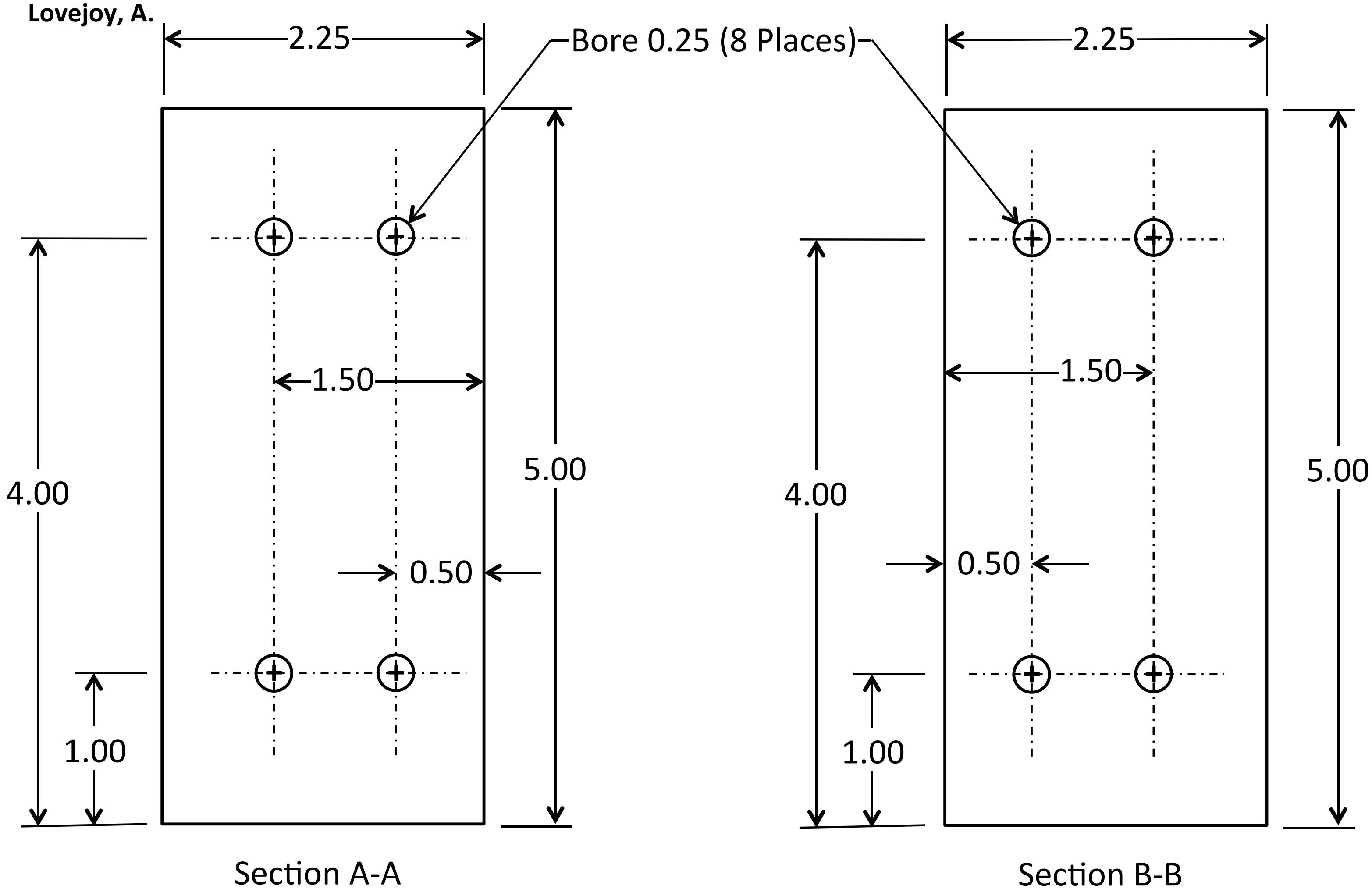
1) Fabricated from 1/8-inch steel sheet stock.
2) Dimensions in inches.
3) Fabricate two (2) pieces.
4) Bend form, approximately 0.125 radius.
5) OML dimensions critical.



Drawing #RCI0012, Sheet 2 (rev. 1)

Part: Track #3 Brace

Lovejoy, A.

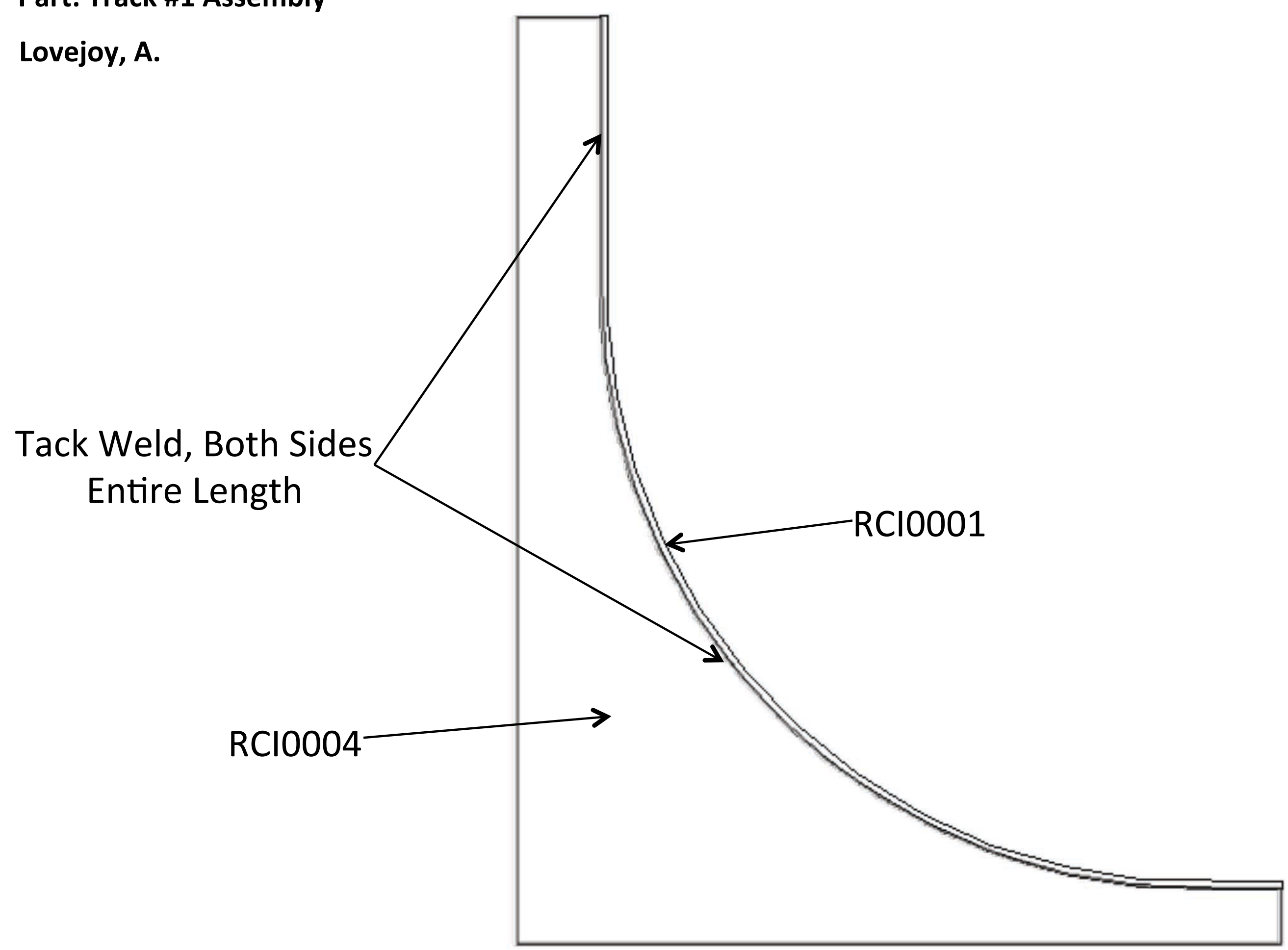


Drawing #RCI0013, Sheet 1 (rev. 1)

Part: Track #1 Assembly

Lovejoy, A.

Notes:
1) RCI0004 centered on RCI0001.
2) Tack welds 1.7-inch spacing.



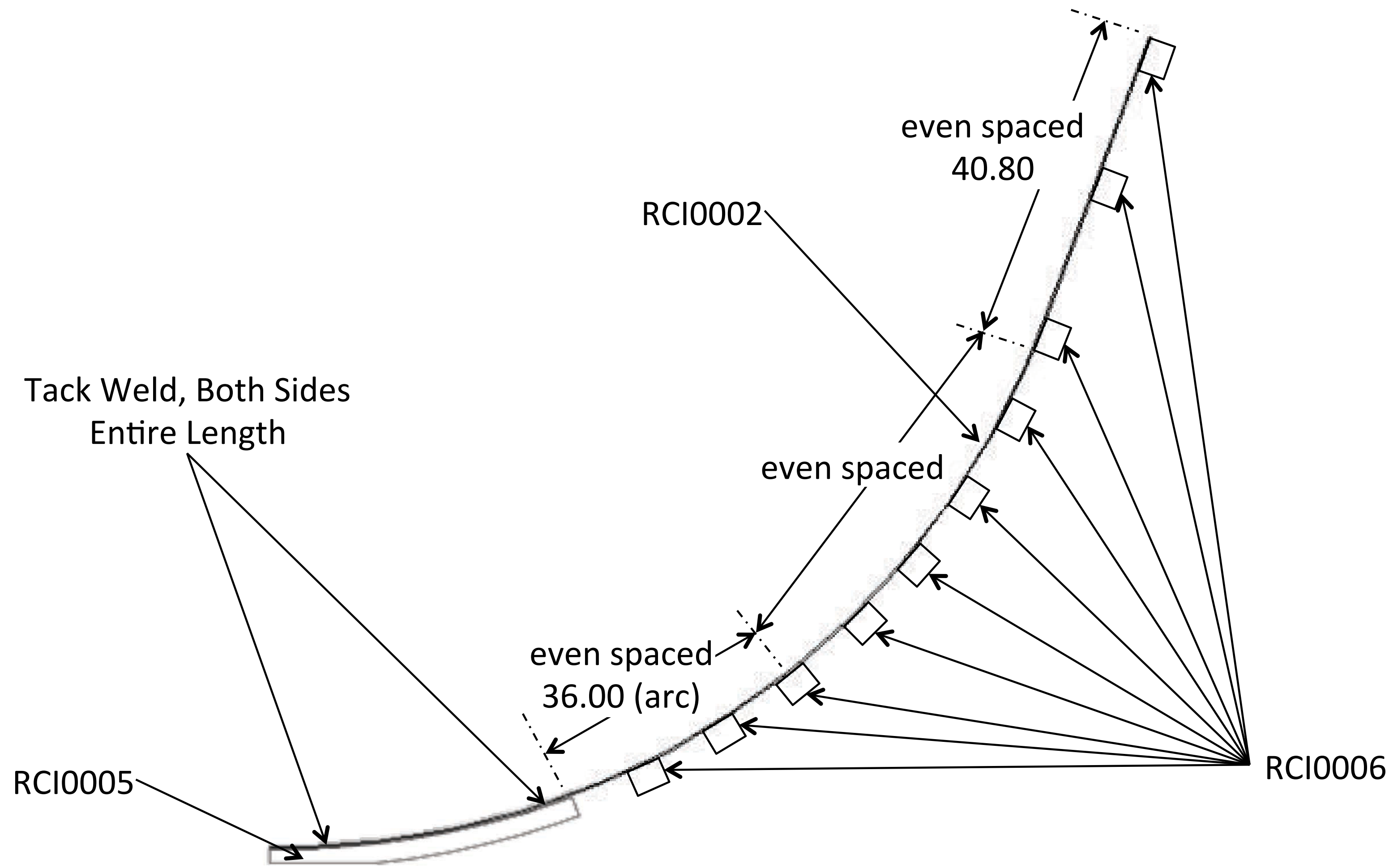
Drawing #RCI0014, Sheet 1 (rev. 2)

Part: Track #2 Assembly

Lovejoy, A.

Notes:

1) RCI0005 flush to end and centered on RCI0002.
2) Tack weld RCI0005 with 1-in. tack welds @ 6-inch spacing.
3) Tack weld RCI0006 centered on RCI0002.



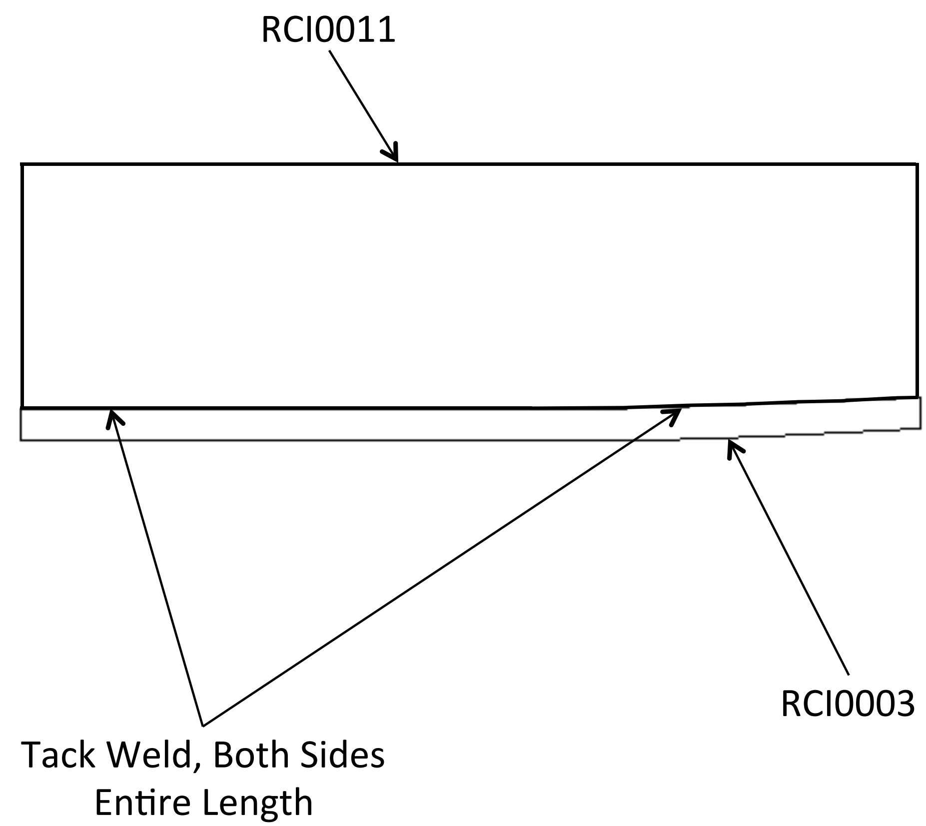
Drawing #RCI0015, Sheet 1 (rev. 1)

Part: Track #3 Assembly

Lovejoy, A.

Notes:

1) RCI0011 centered on RCI0003.
2) Tack welds 1.4-inch spacing.



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14. ABSTRACT

Aircraft structure is required to demonstrate satisfaction of the FAR requirements for Category 1, such as barely visible impact damage (BVID). Typical aircraft structure is impacted using a dropped weight impactor, which can impart BVID to the top surface of the structure. A recent test of a multi-bay box (MBB) composite test article, that represents an 80% scale center section of a hybrid wing body aircraft, required impact to be in a direction other than vertical from above, but still in an direction that is normal to the surface. This requirement eliminated the use of the conventional dropped weight impactor. Therefore, a design study was undertaken to determine the most effective way to efficiently and reliably impact the MBB. The chosen design was a guided weight impactor that is gravity driven. This paper describes the design of the guided weight impactor, and presents the results of its use for imparting BVID to the MBB. The guided weight impactor was seen to be a very reliable method to impart BVID, while at the same time having the capability to be highly configurable for use on other aircraft structure that is impacted at a variety of impact energies and from a variety of directions.

15. SUBJECT TERMS

BVID; Composite structure; Impact

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