Development of Guidelines for In-Situ Repair of SLS-Class Composite Flight Hardware

Thomas P. Weber, Jr.
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Thomas P. Weber, Jr.[1] and Sarah B. Cox[2]
NASA John F. Kennedy Space Center, Florida, 32899

Abstract

The purpose of composite repair development at KSC (John F. Kennedy Space Center) is to provide support to the CTE (Composite Technology for Exploration) project. This is a multi-space center effort with the goal of developing bonded joint technology for SLS (Space Launch System) -scale composite hardware. At KSC, effective and efficient repair processes need to be developed to allow for any potential damage to composite components during transport or launch preparation. The focus of the composite repair development internship during the spring of 2018 was on the documentation of repair processes and requirements for process controls based on techniques developed through hands-on work with composite test panels. Three composite test panels were fabricated for the purpose of repair and surface preparation testing. The first panel included a bonded doubler and was fabricated to be damaged and repaired. The second and third panels were both fabricated to be cut into lap-shear samples to test the strength of bond of different surface preparation techniques. Additionally, jointed composite test panels were impacted at MSFC (Marshall Space Flight Center) and analyzed for damage patterns. The observations after the impact tests guided the repair procedure at KSC to focus on three repair methods. With a finalized repair plan in place, future work will include the strength testing of different surface preparation techniques, demonstration of repair methods, and repair of jointed composite test panels being impacted at MSFC.

I. Introduction

The purpose of composite repair development at KSC (John F. Kennedy Space Center) is to provide support to the CTE (Composite Technology for Exploration) project. This is a multi-space center effort with the goal of developing bonded joint technology for SLS (Space Launch System) -scale composite hardware. Since composites and adhesively bonded joints currently cannot be designed through analysis the way metal components can, testing must be conducted to fully characterize these designs for flight structures. This project is looking to develop the analysis tools in order to reduce the amount of testing and improve the predictability and reliability of bonded joints. At KSC, effective and efficient repair processes need to be developed to allow for any potential damage to composite components during transport or launch preparation. The focus of the composite repair development internship during the spring of 2018 was on the documentation of repair processes and requirements for process controls based on techniques developed through hands-on work with composite test panels. The Repair Test Panel section focuses on the first composite test panel fabricated during the internship. The Impact Testing section discusses the results of impact tests conducted at MSFC (Marshall Space Flight Center) and how these results guided the repair procedure at KSC. The development of a repair plan based on the impact testing results is discussed in the Development of a Repair Plan section. Finally, the fabrication of the second and third panels as well as the strength testing of different surface preparation techniques is focused on in the Surface Preparation section.

[1] Engineering Intern, Materials Science Branch, KSC, The Ohio State University
[2] AST, MECHANICS OF MATERIALS & STRCTR, Materials Science Branch, NE-L4, KSC

II. Repair Test Panel

A. Repair Test Panel Fabrication

To initiate the development of a composite repair procedure, a composite test panel needed to be fabricated. The repair test panel, designated Panel 001, was laid up with six plies in a $[45,90,0]_s$ configuration. 12” x 18” plies were cut from a roll of CYCOM 5320-1/T650 8HS prepreg to make the panel. The debulk layup process for the panel consisted of a fifteen minute debulk for the first ply, a fifteen minute debulk for the second, third, and fourth plies, and the final debulk and cure cycle for the entire panel (plies one through six). The vacuum bagging schedule for Panel 001, shown in Fig. 1, consisted of a layer of porous Teflon release film between the laminate and the tool and overtop of the laminate. Tacky tape dams coated in fiberglass boat cloth surrounded the edge of the laminate to prevent the edges from crimping and provide edge breathing during the cure. A layer of perforated P3 film was placed over the Teflon release film and a nylon breather cloth was placed over the laminate and the tool. A vacuum port was placed over the breather cloth and a layer of nylon bagging film was placed over the entire tool and secured with tacky tape around the edges. During the first debulk process, a bleeder layer was erroneously not used immediately under the breather cloth which resulted in nylon “fuzz” from the breather clinging to the panel through the perforated holes of the P3 film. This mistake was corrected for future debulks and cures. After remaining under vacuum for twenty-three hours, Panel 001 was cured at 250°F for three hours. When removed from the oven and debagged the next day, Panel 001 appeared to have significant surface porosity for an unknown reason. It was later discovered during the application of the doubler that the apparent surface porosity was actually a result of the panel not being entirely cured.

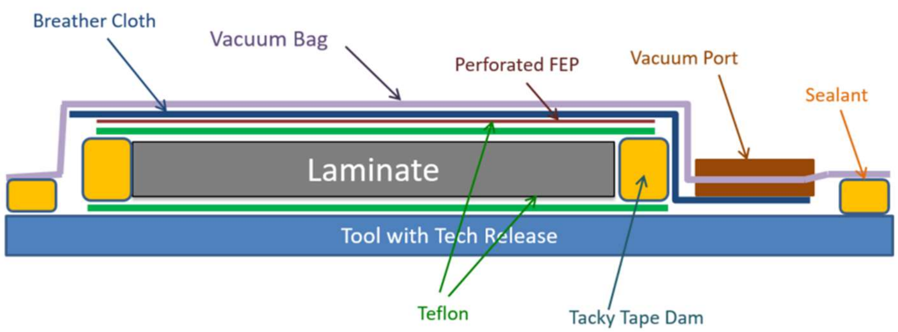

Figure 1. Panel 001 Debulk Bagging Schedule

B. Doubler Application to Repair Test Panel

After Panel 001 had been fabricated, a doubler was applied over the top of the panel according to the specifications established by Marshall Space Flight Center (MSFC) to simulate the bonded joint being tested and analyzed by the CTE project. The doubler was fabricated using strips of varying width of CYCOM 5320-1/T650 8HS prepreg to create a four-ply layup all in a 45 degree configuration. Prior to the application of the doubler onto Panel 001, a layer of film adhesive [FM209-1M] was first placed on top of the panel. The doubler required only a final debulk and cure cycle. The vacuum bagging schedule for the doubler, shown above in Fig. 2, consisted of a layer of solid nylon bagging film between the panel and the tool surface, a layer of perforated P3 release film over the entire panel (including the doubler), a layer of peel ply over the first P3 layer, an additional layer of P3 release film over the peel ply, a nylon breather cloth over the panel and the tool, a vacuum port over the breather cloth, and a final layer of solid nylon

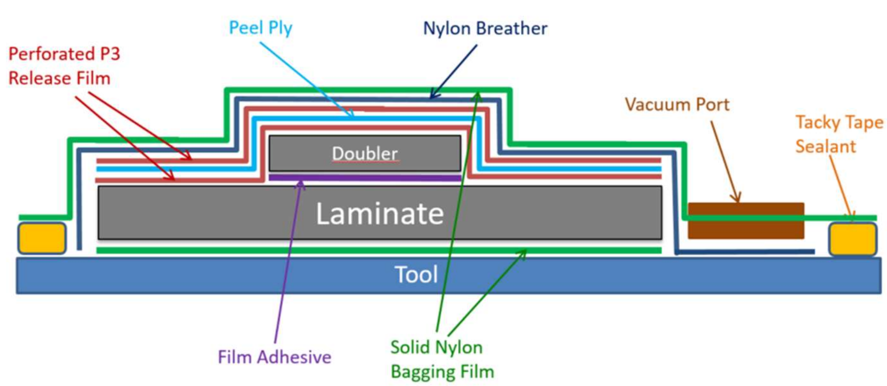

Figure 2. Panel 001 Doubler Bagging Schedule

bagging film over the entire panel and tool secured at the edges with tacky tape. Fiberglass boat cloth strips were added to cover the jagged edges of the panel to protect the bagging film from being punctured. Prior to being left under vacuum for a minimum of sixteen hours, the vacuum bag for Panel 001's doubler was observed to have a very slow leak. This leak was decided to be insignificant due to consistent vacuum pressure being provided by the vacuum pump and the doubler layup was left under vacuum for eighteen hours and ten minutes. Panel 001 with the doubler layup was then cured in the oven at 250°F for 3 hours. Upon debagging the panel the next morning, "fuzz" from the nylon breather cloth was found clinging to the top of the panel. This was the result of the two layers of perforated P3 release film and the layer of peel ply being erroneously placed so as to only cover the doubler rather than the entire panel as well as the discovery that the panel had not been previously fully cured. After this additional cure cycle to the panel, the tool surface of Panel 001 no longer had the previously apparent surface porosity and instead appeared as expected with a smooth, glossy finish on the panel's tool surface.

C. Repair Test Panel Cutting

Panel 001 with the newly bonded doubler was then sectioned off to be cut into smaller sample panels for damage and repair testing. As depicted in Fig. 3, the outer 0.5 inch perimeter of the panel was sectioned off to be discarded, an additional 0.5 inch perimeter was to be kept for microscopic imaging including four corner pieces to be mounted and polished, and the remaining panel was cut into two smaller test panels. Upon initially cutting into Panel 001 at the KSC Prototype Development Lab (PDL) however, the outer 0.5 inch perimeter cuts were difficult to make and were found to be leaving a jagged, "chewed-up" edge on the panel. When the saw blade reached the doubler, the panel was even significantly more difficult to cut. The cause of this difficulty in cutting the panel was due to the panel only receiving the 250°F cure without also undergoing the 350°F post cure. Consequently, the decision was made to put Panel 001 through a post-cure cycle prior to any further cutting which consisted of curing in the oven at 250°F for 2 hours, ramping to 350°F, and curing at 350°F for 2 hours before ramping down. The cuts made to Panel 001 after the post-cure were far cleaner and did not resist the motion of the saw blade at all. The outer 0.5 inch perimeter of the panel that was initially to be discarded and had not been put through the post-cure cycle was kept to be compared with the samples from the inner 0.5 inch perimeter that had gone through the post-cure cycle.

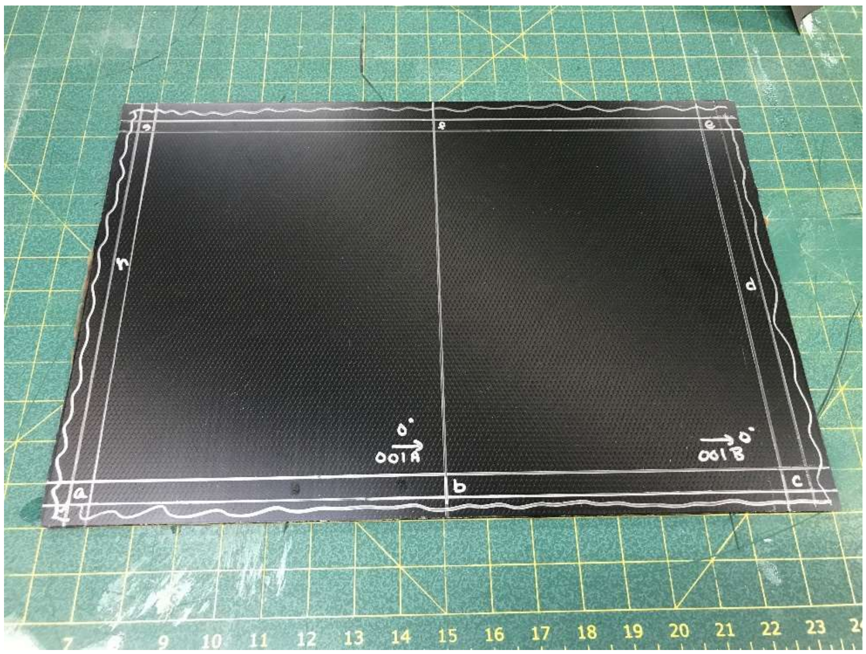

Figure 3. Tool Side of Panel 001 with Cut Lines Drawn

III. Impact Testing

Prior to beginning repair work on the composite test panels, impact tests needed to be conducted on the panels to understand where and how extensive the damage was in the laminate at varying impact energies. Impact tests were to be conducted on the CTE-301 jointed panel by Alan Nettles at MSFC. The panel's configuration was essentially two eight-ply facesheets on each side of aluminum honeycomb with a doubler bonding the panel's splice. The first round of impacts were set at relatively low impact energies, 2, 4, and 6 ft-lbs, with the goal of establishing a Barely Visible Impact Damage (BVID) level directly over the splice. The purpose of establishing a BVID level is to have a set limit of the energy required to yield visible damage; this level will be used as the threshold between undetected damage which must maintain enough residual strength to meet design requirements and detectable damage which will necessitate a repair. After the first set of impact tests, the BVID level was set at 6 ft-lbs since the damage was just visible in normal room lighting conditions from a few feet away which literature has shown to be relatively standard visual inspection criteria. After the visual inspection, all impact locations received Non-Destructive Evaluation (NDE) using thermographic imaging, and then were cut through the damage area in order to evaluate the cross section of the panel. Cross sectional views showed the damage to be almost entirely in the facesheet of the panel with slight core crushing rather than the expected outcome of damage mainly in the doubler. This finding altered the original intended repair plan and necessitated damage removal that extended further into the damaged facesheet of the panel. Further impact testing was conducted with three more 6 ft-lb hits directly over the splice of the panel to ensure repeatability and validation as the BVID level. Additionally another round of 2,4, and 6 ft-lb hits were conducted offset from the splice to compare damage with hits directly over the splice. Inspections revealed that the majority of the damage remained in the facesheet rather than the doubler and that the offset impacts appeared to have produced slightly more delamination than the hits directly over the splice. Based on this testing, it was decided that the impact testing of the test panels was to be conducted at 6 ft-lbs and the impacts would occur offset of the panel's splice.

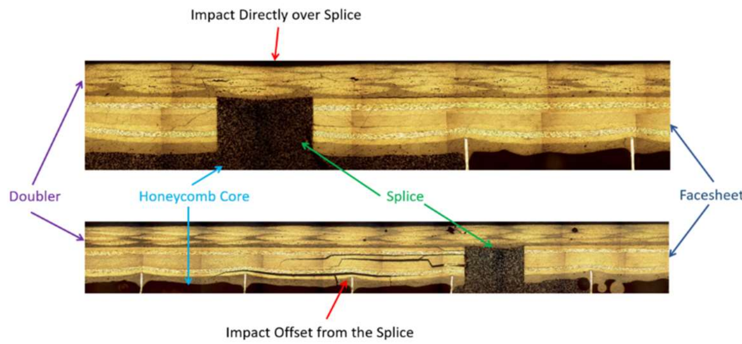

Figure 4. Examples of Panel Cross Sections Depicting 6 ft-lb Impacts Directly over the Splice and Offset from the Splice

IV. Development of a Repair Plan

The next important step working towards the development of a repair procedure was to consider different repair methods and to develop a plan for testing these repair methods. The initial plan for repair was to scarf away damage in the doubler and apply a repair patch accordingly. Scarfing methods included tapered or stepped repairs. Practicing of these methods was conducted at the PDL using handheld disc sanders. An example of a tapered scarf practice panel with visible plies in the doubler is show in Fig. 5. After evaluating cross section views of the impact test samples and observing damage mainly in the facesheet, however, additional repair options needed to be considered. Revised repair options that were considered included bonding a repair doubler over the existing damaged doubler, scarfing away damage only in the doubler and applying a patch, and removing and replacing all of the damage in the doubler, facesheet, and honeycomb core. Additionally, a composite repair kit being developed under NASA Phase 2 SBIR/STTR funding by NONA (No-Oven, No-Autoclave) Composites, LLC was added to the list of considered repair options. All repair options would be subject to the same strength tests after repair completion which consisted of axial edgewise compression, hoop edgewise compression, and hoop tension tests. After deliberation and considering input from project leads at various other NASA locations, two repair plans were established each consisting of the same three repair options: bonding a repair doubler over the existing doubler, removing and replacing all of the damage in the doubler, facesheet, and honeycomb core, and the NONA repair kit. One repair plan, shown below in Table 1, was labeled the "qualified" repair plan and involved five repair samples for each combination of a repair option and strength test plus an additional repair sample to demonstrate each repair option resulting in a total of 48 repair samples.

Figure 5. Tapered Scarfing on Test Panel Doubler

Table 2. Qualified Repair Plan

	Demonstration	Axial Edgewise Compression	Hoop Edgewise Compression	Hoop Tension
Doubler bonded to existing doubler	1 sample	5 samples	5 samples	5 samples
Full damage removal and repair	1 sample	5 samples	5 samples	5 samples
NONA repair	1 sample	5 samples	5 samples	5 samples
Total	48 samples			

The main benefit of the qualified repair plan would be establishing a statistical value based on repeatability of the repair. It was decided to go with the other repair plan labeled the "CTE-Scope" repair plan, shown below in Table 2. The CTE-scope repair plan consisted of one repair sample for each repair option/strength test combination plus the optional demonstration repair samples resulting in a total of nine test samples plus three demonstration samples.

Table 1. CTE-Scope Repair Plan

	(Demonstration)	Axial Edgewise Compression	Hoop Edgewise Compression	Hoop Tension
Doubler bonded to existing doubler	(1 sample)	1 sample	1 samples	1 sample
Full damage removal and repair	(1 sample)	1 sample	1 sample	1 sample
NONA repair	(1 sample)	1 sample	1 sample	1 sample
Total	9 samples (+3 samples)			

While the CTE-scope repair plan would not allow for repeatability, this plan was much more in line with the available resources since only nine test specimens were to be received from MSFC. The three demonstration samples could potentially be made from spare/reject panels. Additionally, the CTE-scope repair plan would take far less time to complete and would prove the concept of the repair.

V. Surface Preparation

The preparation of the laminate surface prior to bonding was a crucial step to be analyzed so as to ensure the most effective bonding surface that would provide the strongest bond possible. The main focus of this part of the project was on simple surface preparation methods such as hand abrasion and solvent wipes. More advanced methods like laser ablation and plasma treatment were not reasonable considerations at that point since they were more expensive, required larger equipment, and were potentially difficult to implement in a "hard to reach" launch pad configuration. It was decided that surface preparation would be tested using the degree of abrasion and the usage of a solvent wipe (Isopropyl Alcohol) as variables. To test different surface preparation methods, a new composite panel needed to be fabricated.

A. Panel 002 Fabrication

Panel 002 was designated to be cut into strips to form lap-shear tests to be used to test the effectiveness of different surface preparation methods. The panel was laid up with eight plies in a [0]8 configuration. 18” x 11” plies were cut from a larger scrap pieces of CYCOM 5320-1/T650 8HS prepreg to make the panel. The debulk layup process consisted of three fifteen-minute debulks for the first ply, second, third, and fourth plies, and fifth, sixth, and seventh plies, respectively. The eighth ply was then applied, Panel 002 was moved to the oven, and it was left under vacuum pressure for nearly eighteen hours. The debulk bagging schedule for Panel 002, shown below in Fig. 6, consisted of a layer of solid nylon bagging film between the laminate and the glass tool, a layer of perforated P3 film over the laminate, a layer of Teflon release film over the P3, a nylon breather cloth over the Teflon, and a solid nylon vacuum bag over the entire glass tool. Additionally, dams made from tacky tape and fiberglass boat cloth surrounded the edge of the laminate to prevent the edges from crimping and to allow for edge breathing. After the eighteen hour debulk, the oven was then turned on for a cure cycle which included three hours at 250°F, a ramp up to 350°F, and two hours at 350°F. The bagging schedule for the oven cure was the same as the bagging schedule for the debulks except for a fiberglass bleeder replacing the Teflon layer over the laminate. After debagging the panel after the oven cure, it was discovered that the solid nylon bagging film between the laminate and the glass tool had sealed to the bottom of the panel and was extremely difficult to remove. It is suspected that the bagging film used was approaching its maximum use temperature which caused a physical change allowing it to adhere to the laminate.

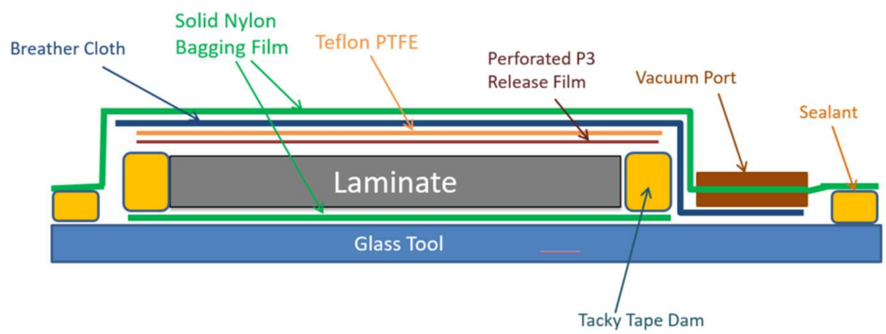

Figure 6. Panel 002 Debulk Bagging Schedule

B. Panel 002 Cutting

Figure 7 shows how Panel 002 was sectioned into smaller rectangular pieces for the lap-shear tests in accordance with the dimensions for the lap-shear test components given in ASTM D 3165 “Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies.” Each numbered column will be cut into smaller 1” wide strips after performing a particular surface preparation. The columns were made 3.3” wide to allow for additional tolerances for the band saw blade used to cut the panel. The lettered rows of Panel 003 correspond to the different components of the lap-shear test. Row A is 3.5” long, Row B is 4” long, and

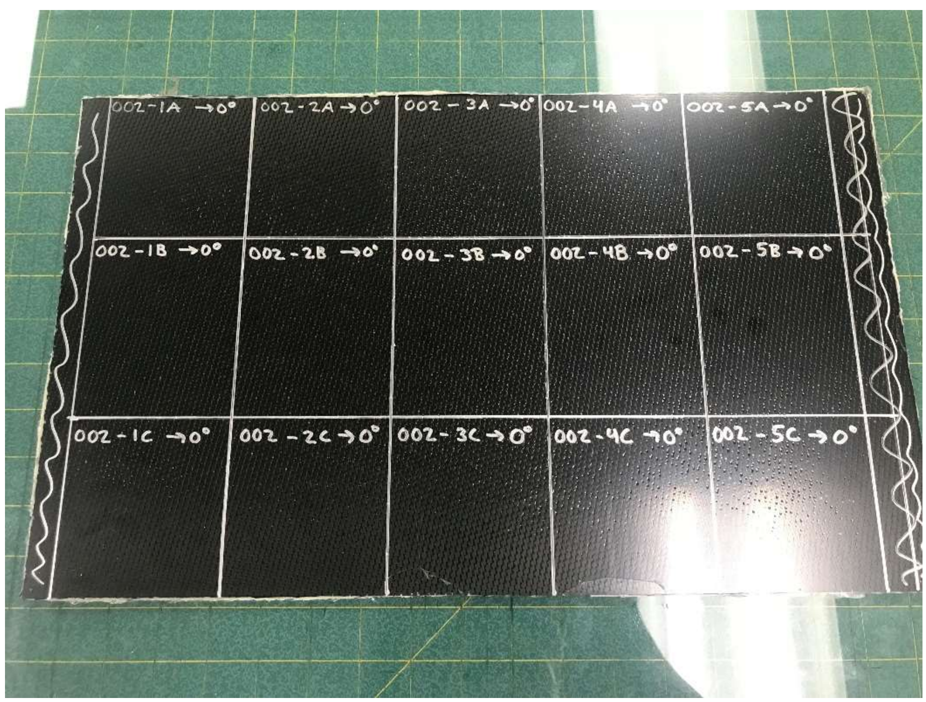

Figure 7. Tool Side of Panel 002 with Cut Lines Drawn

Row C is 3.5” long. An additional 4” section of prepreg will be cocured to the prepared surfaces of Row B to represent the repair doubler being bonded to the part; each column (-1 through -5) will receive a different surface prep in order to test the bond of different surface preparation techniques.

C. Panel 003 Fabrication and Cutting

Panel 003 was laid up to match the configuration of Panel 002 exactly so that the surface preparation lap-shear testing could be continued. The only difference in the fabrication process of Panel 003 was that Teflon release film was placed between the laminate and the glass tool to avoid the issue of the nylon bagging film clinging to the panel which was experienced during the fabrication of Panel 002.

VI. Conclusion

The purpose of the Composite Repair Development Spring 2018 internship at KSC was to document and help develop repair processes for composite bonded joint technology through hands-on work with composite test samples. A repair test panel was first fabricated to practice scarfing and repair. Inspection of impact tests at MSFC showed that the majority of damage to the laminate was in the facesheet which lead to the development of an altered repair plan that considered the option of removing damage down to the honeycomb core and facesheet level in addition to a simple repair doubler and the NONA repair kit. Additional panels were fabricated to create lap-shear tests to analyze the strength of bond of different surface preparation techniques. Future work will include the selection of the most effective surface preparation method, practice of different repair options on CTE-301 jointed panels from MSFC, and higher energy impact testing. The eventual goal, if needed, is to be able to apply these repair methods to composite bonded joints in application on SLS-scale composite hardware.

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