

Supplementary Materials

This Supplementary Materials shows how the thermoplastic blades were instrumented, with detailed steps in the captions of each figure.



Figure S1. Blade 3 HP Strain Gage Layout - This step demonstrates typical marking a straight line on the Spar Cap Center (SCC) from blade root to tip. This step ensures consistent strain gage placement along the spar cap. Initial marks are measured in at the root and tip of the blade. Between these marks a large metal ruler is used to draw a straight pencil line between marks. All 6 blade halves were measured and marked using this procedure, and specifically for the tip we measured in 96mm in from leading edge and root we measured in 189mm from the leading edge. Note: Strain gage manufacturer Micro-Measurements (MM) recommends usage of a 4H pencil for burnishing marking lines. Photo by Andrew Simms / NREL.

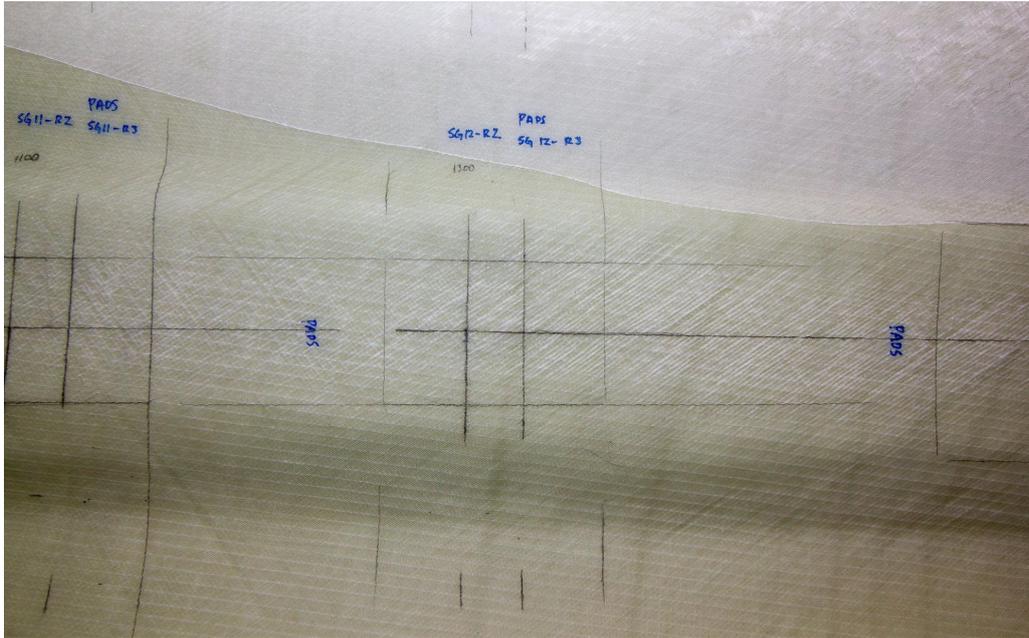


Figure S2. Example of typical full bridge (Wheatstone bridge) strain gage layout prior to sanding. For consistency of measurement during this step we measure from the blade tip to the strain gage location. At the gage location and 25mm towards the tip we burnish crosshairs using a 4H pencil. Additionally, we mark a rectangle that is 68mm wide by 72mm tall which denotes the protective coating (MM M-Coat JA) area. For each full bridge location, accounting for both strain gages, the final rectangle measures out to 68mm wide by 97mm tall. We also extend layout lines past the gage area as the marks will be removed during sanding. Photo by Andrew Simms / NREL.



Figure S3. Strain gage location after sanding. Surface should be hand sanded smooth and flat slightly beyond marked protective coating area. Instructions for this project specified a 180 grit surface finish. Note: Thermoplastic materials tend to “gum” up sand paper and require extra time and materials. Photo by Andrew Simms / NREL.

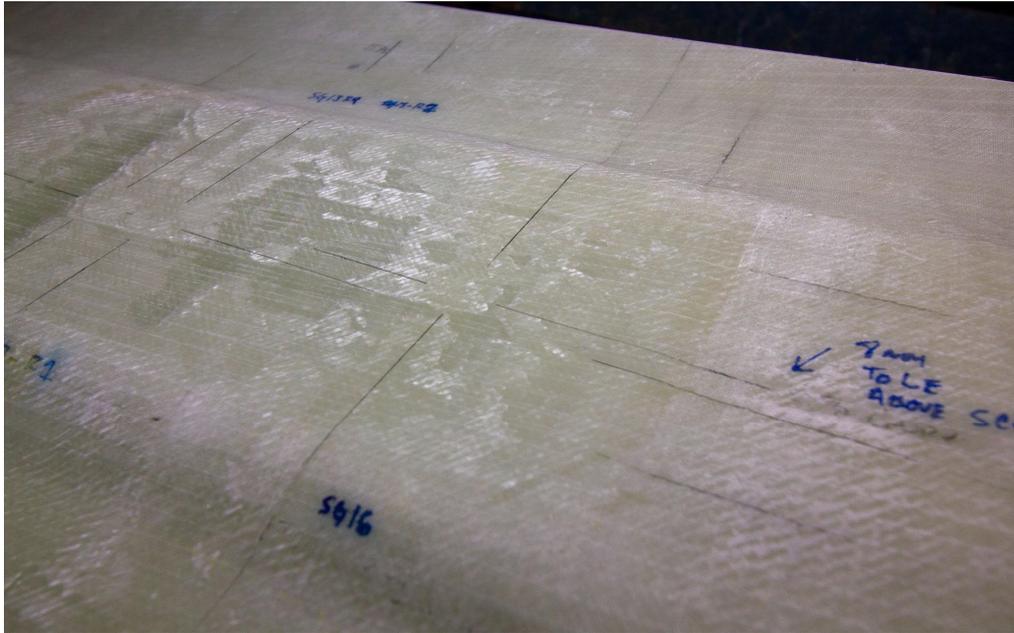


Figure S4. Strain gage location post conditioning with layout lines. Conditioning is done per MM M-Bond 200 Application instructions including wet sanding using MM M-Prep Conditioner, neutralizing with MM M-Prep neutralizer and final cleaning with MM GC-6 Isopropyl Alcohol. For this project MM degreaser was not used as it adversely affects the thermoplastic substrate. Note that layout lines get close to but do not extend into strain gage application area. A typical buffer of 3-5mm between the gage and layout lines is best practice. Photo by Andrew Simms / NREL.

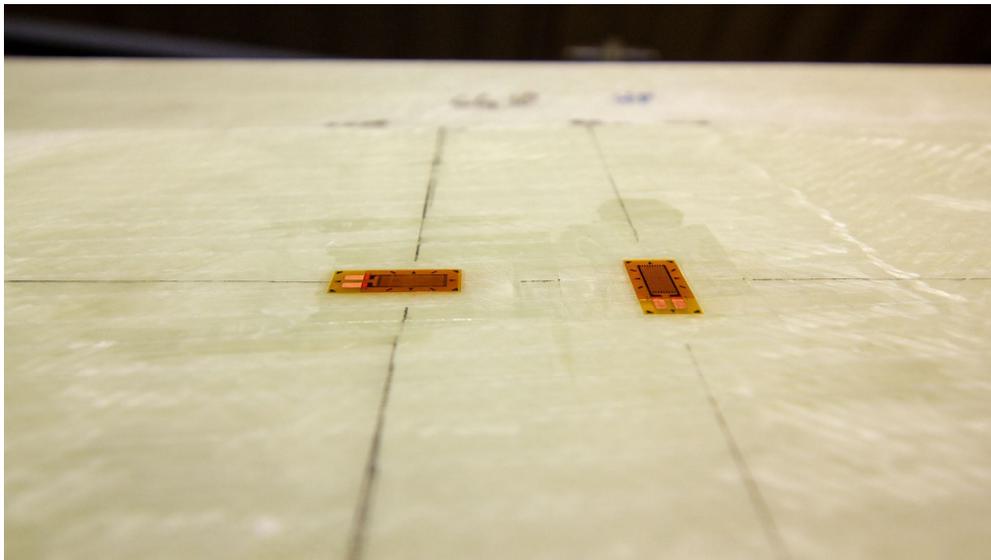


Figure S5. Strain gage after glue application. For this project MM M-Bond 200 was used as strain gage adhesive. M-Bond 200 is a room temperature cure, quick drying, cyanoacrylate glue that is commonly used for short term strain gage adhesion. Note: While this glue worked for this project, Micro-Measurements offers a room temperature cure two part strain gage adhesive, AE-10, that may offer better long term adhesion, but is more difficult and time consuming to install. Photo by Andrew Simms / NREL.

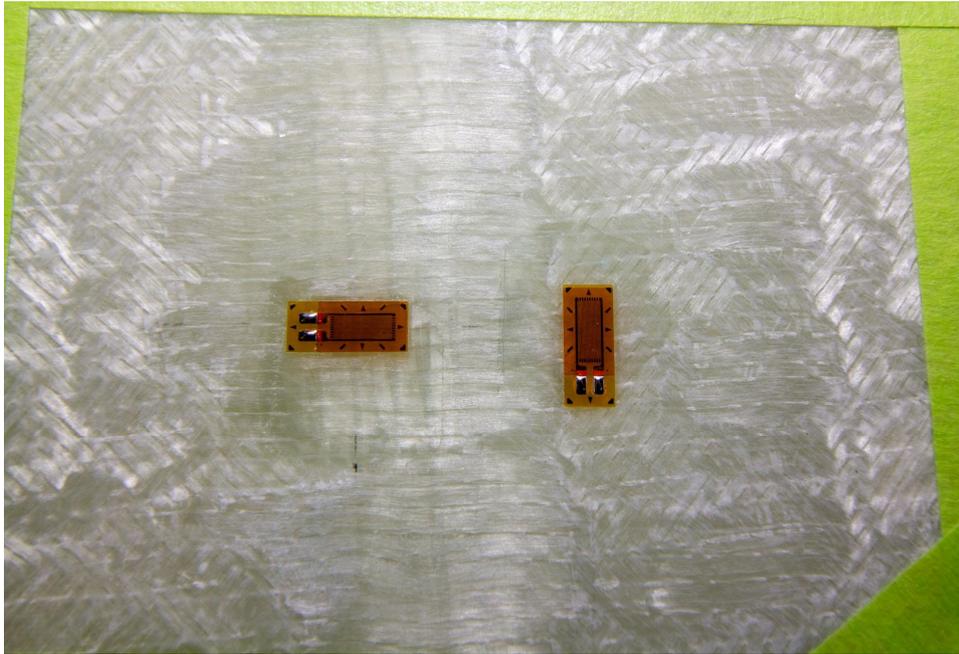


Figure S6. Strain gage with pads solder in preparation for cable attachment. Before soldering the pads are prepped with MM M-Flux FAR and After soldering the pads and gage are thoroughly cleaned with MM M-Line Rosin Solvent and MM GC-6. Note: the shininess of solder on pads, which denotes a proper soldering job. Photo by Andrew Simms / NREL.

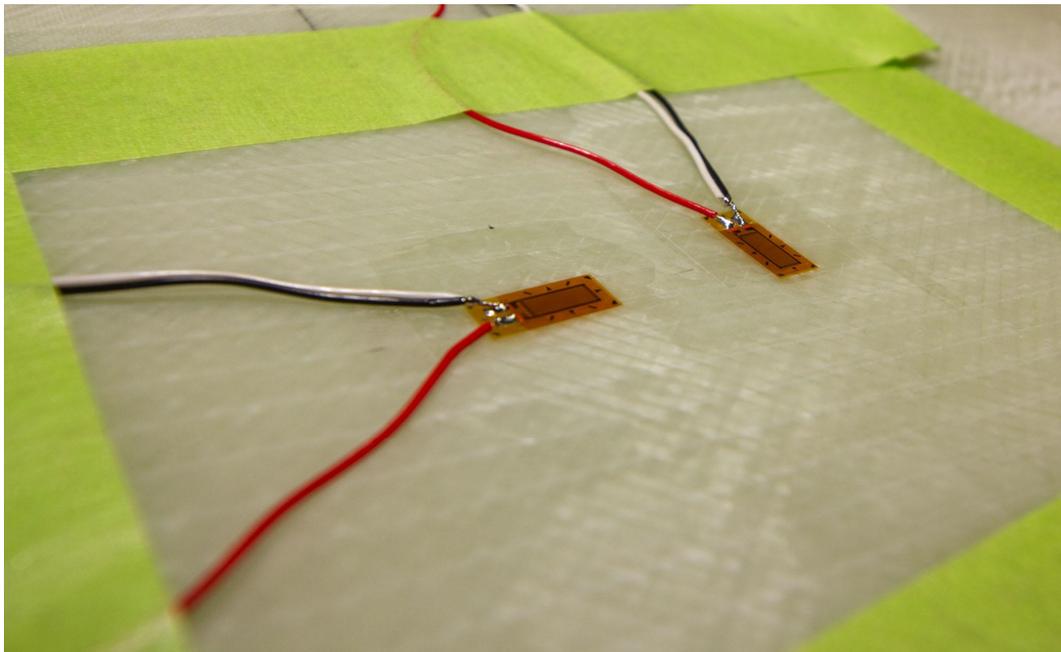


Figure S7. Strain gages with MM 330-FTE (3 conductor twisted 30 AWG with etched Teflon™ jacket) cables attached. Etched Teflon™ jacket cable is specified as it provides good resistance to water and bonds properly to MM M-Coat JA. Prior to soldering cables are untwisted, flattened, and tinned. During the tinning process the black and white wires are soldered together. To avoid overheating the solder pad the white wire is wrapped around the black wire before the solder pad location and soldered in place. Cables are held in position for soldering using MM PDT-3 drafting tape. After soldering the pads, gage, and cables are all carefully cleaned with MM M-Line Rosin Solvent and MM GC-6. Once this step is complete a resistance check should be performed to confirm nominal operation of the strain gage. For quality control (QC) purposes, resistances between the red and black, red and white, and white and black cables should all be recorded and verified by a second qualified person. Photo by Andrew Simms / NREL.

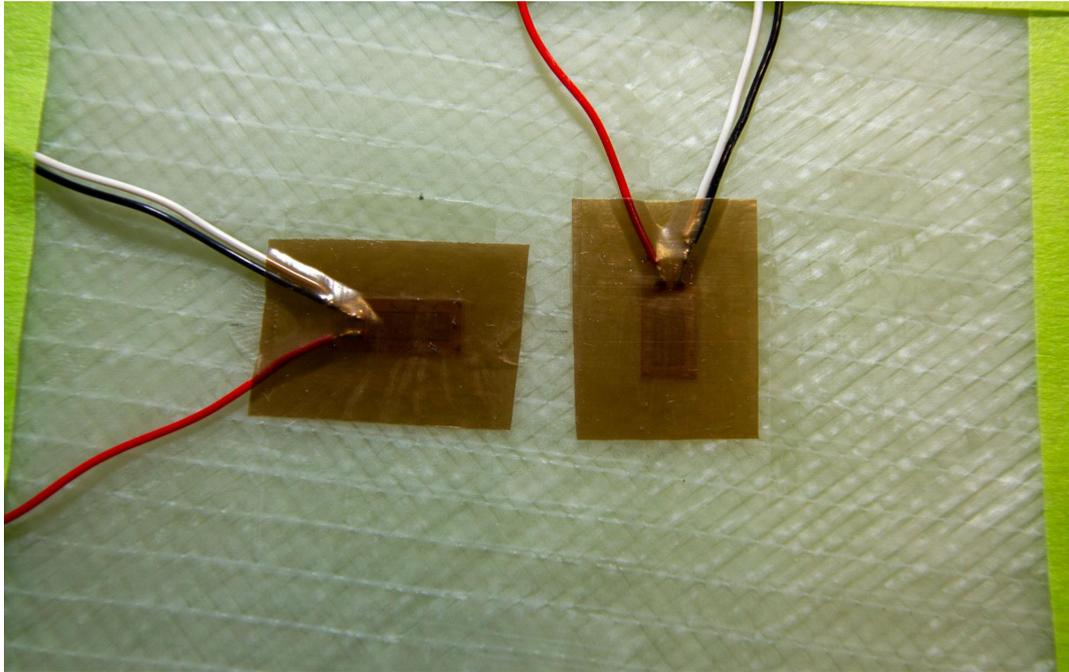


Figure S8. Strain gages with Teflon™ tape applied prior to protective coating application. Per MM JA application instructions, Teflon tape is cut to sit 1/4" outside of the strain gage. Application is done carefully with a cotton swab, pressing the tape into the substrate to ensure adhesion. Note: Using a cotton swab leaves behind some cotton residue which must be cleaned with MM GC-6 IPA. A tip to avoid this residue is to cover the head of the cotton swab with clear tape. Photo by Andrew Simms / NREL.

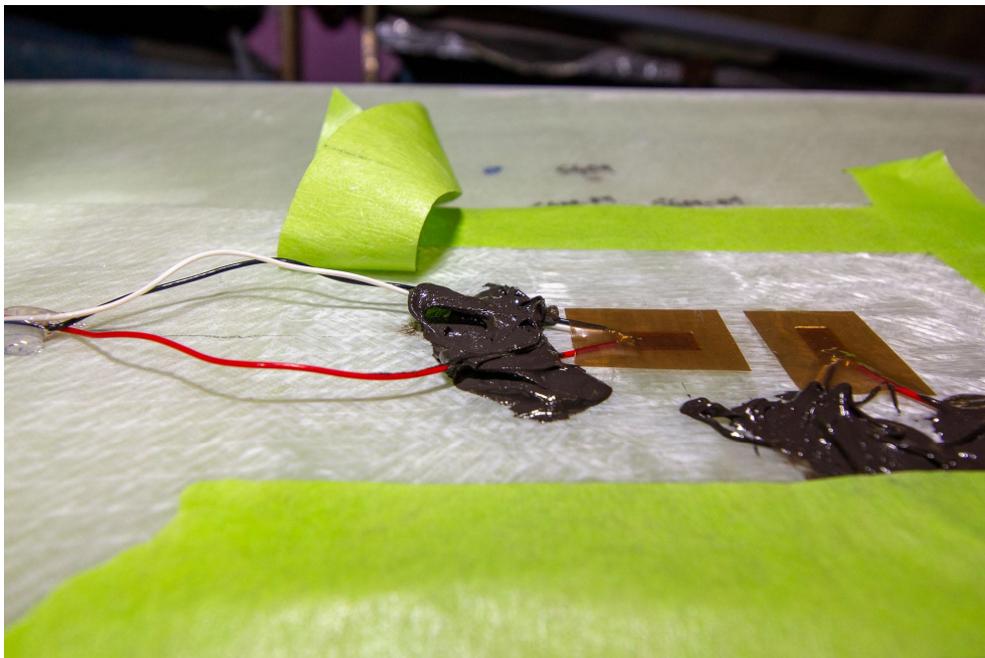


Figure S9. Application of protective coating M-Coat JA under cables. During this step we strictly follow MM's "Application of M-Coat JA Protective Coating" instructions. Note: MM recommends specifically applying JA under cables. In practice this is a delicate operation and must be done with care to avoid damage to strain gage cable attachment locations. A recommendation prior to this step is to hold down cables at the gage using the wooden end of an MM CSP-1 cotton swab. Photo by Andrew Simms / NREL.



Figure S10. Continued application of M-Coat JA. Recommended application technique is to work from the gage outward to prevent lifting the edges of the Teflon tape. A small metal spatula is used to press JA into the surface to ensure proper bonding and long lifespan. Note: tape is carefully pulled away while JA is still wet. A high tape angle is recommended to maintain integrity of the edges. After tape is pulled from the edges, drafting or Kapton tape is used to hold cables down for the duration of the curing process. Photo by Andrew Simms / NREL.



Figure S11. M-Coat JA protective coating after application. Note the smoothness of the coating. Great care is taken during smoothing to ensure there are no voids or visible gaps in the coating. At this point another QC check is recommended and can be performed by measuring and recording resistances between the red and black, red and white, and white and black cables. Photo by Andrew Simms / NREL.



Figure S12. Wiring harness detail of 330-FTE strain gage cables. Lacing wire was used to keep cable bundle size as small as possible. During this step it is critical to keep the wire clean and dirt free. Cables are carefully laid out straight and bundled in this position to avoid twisting cable. Note: Prior to bundling cables are precisely measured and labeled. During this step cables are not shortened but are carefully bundled together (shown in the middle of the photo). To maintain consistent resistances for all cables at no point are cables cut shorter. Another QC check is recommended after completion of the wiring harness. Photo by Andrew Simms / NREL.



Figure S13. Strain gage cables entering/exiting LP side of Blade 2. Prior to this step the 4 sets of MM 426 FTE (4 conductor twisted 26 AWG with etched Teflon™ jacket) cables are bundled in two layers of heat shrink. Prior to heat shrinking, the cables are carefully measured, labeled, laid out straight, cleaned, and taped together with Kapton tape. Two types of heat shrink are necessary, thin wall adhesive lined, and heavy wall (adhesive lined if possible). Use thin-walled adhesive lined heat shrink for the first layer. Push all cables through the heat shrink. IPA may be used as a lubricant if pushing is difficult. Then use a heat gun to carefully activate the heat shrink, slowly working from one end of the cable to the other. This assembly is then pushed through a second layer of heavy wall heat shrink (adhesive lined if available, but heavy wall is important). A heat gun is again used to carefully activate the heat shrink. Some hands-on experimentation may be necessary to ensure that the bundle size is correct. For this project the installer used one continuous piece on heat shrink for each layer. In practice pushing small cables through heat shrink is difficult and using shorter pieces of heat shrink and sleeving the joints with layers of heat shrink may adequate and require less effort. Photo by Andrew Simms / NREL.



Figure S14. Full view of completed strain gage instrumentation installed on Blade 1 low pressure skin prior to bonding and foam fill of the blade cavity. Note: Full bridge splices are not complete at this time to allow for flexibility in the blade manufacturing process. Also note that cables must be long enough to exit the blade and allow working space to complete the full bridge splice. One internal and one external splice were sealed with 3M™ Scotchcast™ 2131 potting compound, as shown in Figure 32. Photo by Andrew Simms / NREL.

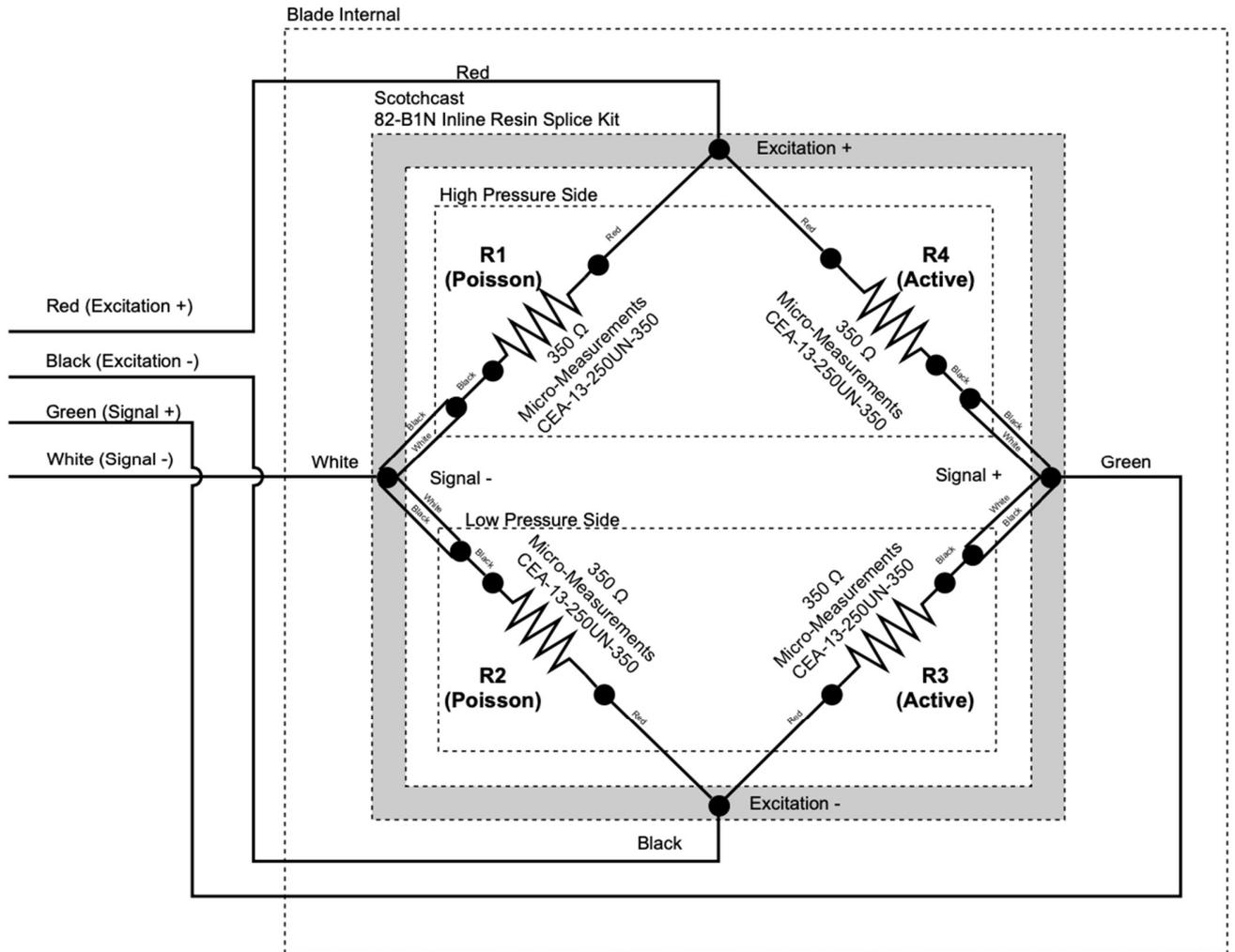
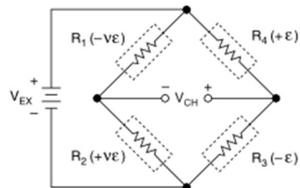


Figure S15. Wiring diagram of Wheatstone bridge based on the National Instruments “Full-Bridge Strain Gage Configuration II” (only bending strain) (National Instruments, 2022). Note that a typical 3 conductor cable is used from the strain gage to the full bridge splice. In practice this useful to measure the resistance of the cable to the individual strain gage but was not strictly necessary for this measurement campaign because components downstream did not require hookup of the sense circuit.

Full-Bridge Type II Circuit Diagram



The following symbols apply to the circuit diagram:

- R_1 is the active strain gage element measuring compressive Poisson effect $(-\varepsilon)$.
- R_2 is the active strain gage element measuring tensile Poisson effect $(+\varepsilon)$.
- R_3 is the active strain gage element measuring compressive strain $(-\varepsilon)$.
- R_4 is the active strain gage element measuring tensile strain $(+\varepsilon)$.
- V_{EX} is the excitation voltage.
- R_L is the lead resistance.
- V_{CH} is the measured voltage.

Figure S16. National Instruments wiring detail of full-bridge strain gages from “Full-Bridge Strain Gage Configuration II” (only bending strain) (National Instruments, 2022).

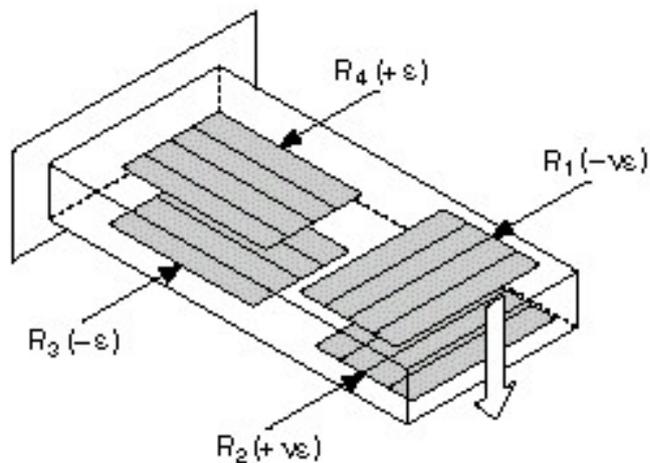


Figure S17. National Instruments layout detail of full-bridge strain gages from “Full-Bridge Strain Gage Configuration II” (only bending strain) (National Instruments, 2022).

Verdant - Full Bridge - Hookup Guide			
Location	From Gages	To DAS	Purpose
HP Poisson	R1 RED	RED	EXC POS
HP Active	R4 RED		
LP Poisson	R2 RED	BLK	EXC COM
LP Active	R3 RED		
HP Active	R4 BLK	GRN	SIG POS
	R4 WHT		
LP Active	R3 BLK		
	R3 WHT		
HP Poisson	R1 WHT	WHT	SIG COM
	R1 BLK		
LP Poisson	R2 WHT		
	R2 BLK		

Figure S18. Full-bridge wiring hookup guide for splicing full-bridge strain gages from individual gages.

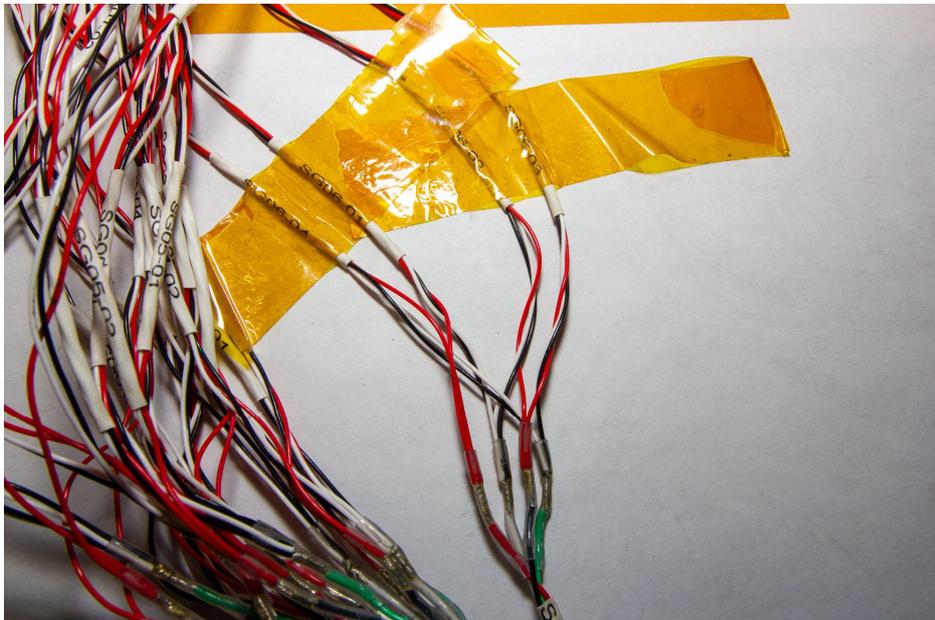


Figure S19. Detail of blade 1 SG 06 full bridge splice. To complete each individual splice a “solder sleeve” connector was applied per manufacture specifications (TE Connectivity CWT-9001). Great care is taken to ensure that solder flows throughout the connection. A QC check is recommended before and after completing the bridge splices. Note: this step requires using a heat gun to activate the solder sleeve and special attention should be paid to the manufacture’s recommendation of the maximum temperature. Additionally, usage of a heat gun tip that guides air around the solder sleeve is strongly recommended. Photo by Andrew Simms / NREL.



Figure S20. Blade 2 full bridge splice prepped for 3M™ Scotchcast™ 2131 application. Scotchcast™ 2131 is a two-part epoxy potting compound typically used for protecting subsea cable splices. Prior to potting, all cables, splices, and mold are cleaned with isopropyl alcohol and put into a plastic mold. In this case the jacket of cable exiting was sanded with 80 grit sand paper to promote adhesion. Cables are pulled tight and taped at each exit point with 3M™ Super 33 electrical tape. Great care is taken to ensure that each cable exit is sealed. 2131 is then mixed and poured into the mold per the manufacture’s specifications. The pour is done slowly to avoid air pockets in the mold. Pouring should be done from one spout to let air escape from the other. If any leaks are identified, they can be sealed with electrical tape. At the end fill both pour spouts with any remaining epoxy. Photo by Andrew Simms / NREL.



Figure S21. Wide view of Blade 2 full bridge Scotchcast™ splice post curing. Spouts are cut off with a sharp knife. The clear plastic shell is retained for added protection. Photo by Andrew Simms / NREL.



Figure S22. Detail view of Blade 2 full bridge splices in finished Scotchcast™ mold. Note: the lack of air bubbles within the clear plastic mold indicating a successful application of Scotchcast™ 2131. Photo by Andrew Simms / NREL.



Figure S23. Blade 3 external Scotchcast™ splice, post-deployment. Note that all six Scotchcast™ splices successfully survived the deployment and there are no indications of damage or water ingress. Photo by Andrew Simms / NREL.



Figure S24. Blade 1 with external Scotchcast™ splice visible. Great care is taken to protect cables and splices throughout the manufacturing and shipping process. Also note that connectors are kept in plastic bags to avoid introduction of fiberglass dust or adhesives. Photo by Andrew Simms / NREL.



Figure S25. Blade 1 internal Scotchcast™ splice during blade foam fill process. The splice was not mechanically attached to avoid altering the blade's structural characteristics and the moderately hard fill foam was used to keep the splice in place. Photo by Andrew Simms / NREL.

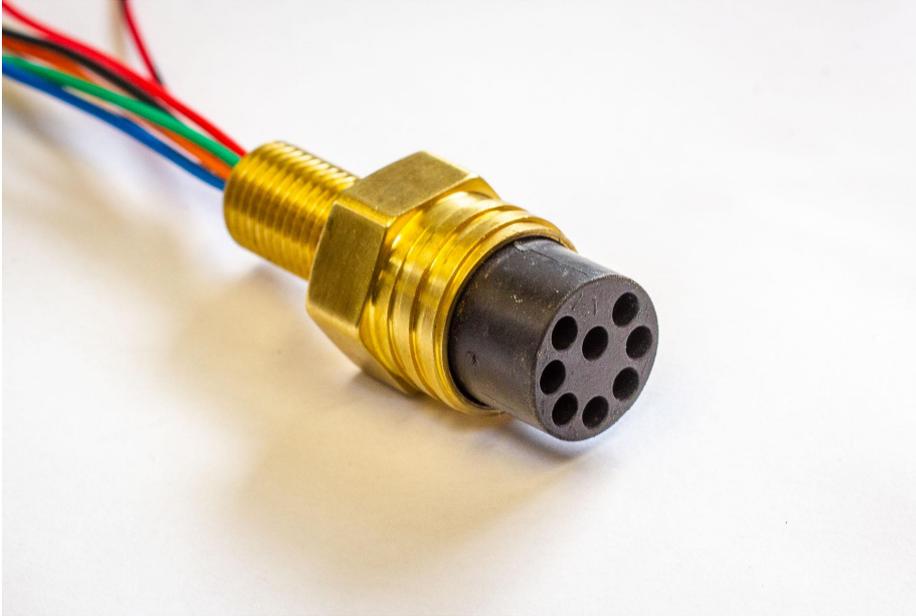


Figure S26. Example of eight-pin SubConn female connector used on NDAQ for strain gage connection.
Photo by Andrew Simms / NREL.

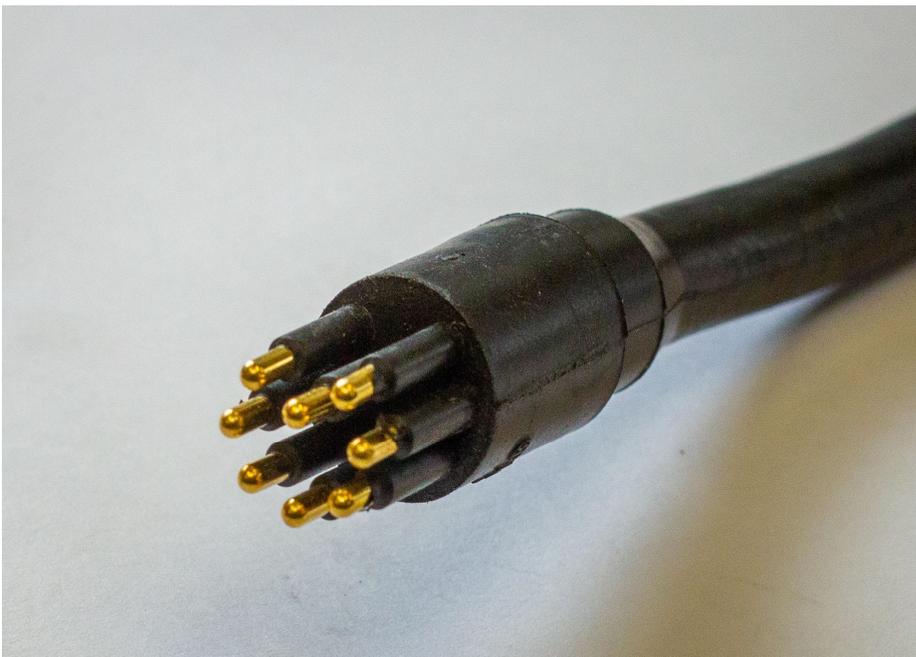


Figure S27. Example of eight-pin SubConn male connector, which was spliced into strain gage cables.
Photo by Andrew Simms / NREL.



Figure S28. Eight-pin SubConn male connector post-deployment. Note that all eight SubConn connectors used for strain gage signals successfully survived the deployment. Photo by Andrew Simms / NREL.



Figure S29. Detail of Blade 3 root foam fill prior to shipment. Scotchcast™ splices are sealed within the foam fill of the blade. Note: cables were wrapped with Teflon™ spiral wrap to provide additional protection for the cable run from the blade through the hub to the NDAQ. Photo by Andrew Simms / NREL.



Figure S30. Photograph of fully instrumented and completed blades in shipping container. Cabling and splices are secured in multiple places to prevent movement and damage during shipping and protected with boxes made of rigid foam insulation. Photo by Andrew Simms / NREL.

VERDANT BLADE 3

MEME MICRO-MEASUREMENTS

FOR COMPLETE TECHNICAL DATA, VISIT WWW.VISHAYPG.COM

GRID RESISTANCE IN OHMS TC OF GAGE FACTOR, %/100°C
350.0±0.3% (+1.8±0.2)

GRID	GAGE FACTOR @ 24°C	TRANSVERSE SENSITIVITY
1	2.110±0.5%	(+0.3±0.2)%
2		
3		
NOM		

HERMAL OUTPUT COEFFICIENTS FOR 2024-T4 ALUMINUM @ G.F. OF 2.00

ORDER	FAHRENHEIT	CELSIUS
0	-1.22E+2	-4.08E+1
1	+3.35E+0	+3.20E+0
2	-2.74E-2	-7.06E-2
3	+5.82E-5	+3.39E-4
4		
5	VERDANT BLADE 3	

FOIL LOT NUMBER	DATE	INSTALLER	
A108AF505	SG14-R2	12/15/20	A. Simms
	SG14-R3	"	"
WORK ORDER NUMBER	DATE	INSTALLER	
02280615	SG13-R2	"	"
35214304	SG13-R3	"	"
	SG12-R2	"	"

ITEM CODE QTY 1 PK CODE RoHS COMPLIANT
MMF003208 (5 pcs) 201929US

COUNTRY OF ORIGIN USA



CEA-13-250UN-350

Figure S31. Strain gage packaging. Note: The installer included the project, gage label, date, and name on the packaging. Photo by Andrew Simms / NREL.

BLADE Z
Post JA
12/7/20

PRE SPILLED
12/7/20
A. SIMMS

2-3 1-3 3-4 2-1 2-4 1-4
0-8 7-8 5-8 6-7 5-6 5-7

Pre JA			Post JA			Full Bridge					
Red-White	White-Black	Red-Black	Red-White	White-Black	Red-Black	Red-White	Red-Black	Red-Green	White-Black	White-Green	Black-Green
SG01-01			351.22	0.84	351.21	263.96	351.44	263.22	263.77	351.50	263.73
SG01-02			350.79	0.85	350.79	263.89	351.20	263.62	263.77	351.51	263.92
SG01-03			351.16	0.84	351.16	263.94	351.20	263.62	263.77	351.51	263.92
SG01-04			350.73	0.84	350.73	263.94	351.20	263.62	263.77	351.51	263.92
SG02-01			351.25	1.02	351.25	264.02	351.74	264.18	263.94	351.77	264.07
SG02-02			351.04	1.02	351.10	264.02	351.82	264.19	263.94	351.77	264.07
SG02-03			351.25	1.02	351.34	264.02	351.82	264.19	263.94	351.77	264.07
SG02-04			351.25	1.02	351.25	264.02	351.74	264.23	264.05	351.75	264.05
SG03-01			351.35	1.34	351.35	264.10	351.84	264.25	264.11	351.90	264.10
SG03-02			351.27	1.34	351.37	264.10	351.84	264.25	264.11	351.90	264.10
SG03-03			351.29	1.35	351.37	264.10	351.84	264.25	264.11	351.90	264.10
SG03-04			351.29	1.32	351.44	264.10	351.84	264.25	264.11	351.90	264.10
SG04-01			351.49	1.20	351.47	264.44	352.24	264.34	264.44	352.29	264.42
SG04-02			351.49	1.20	351.46	264.44	352.24	264.34	264.44	352.29	264.42
SG04-03			352.07	1.20	352.02	264.44	352.24	264.34	264.44	352.29	264.42
SG04-04			351.85	1.20	351.86	264.44	352.24	264.34	264.44	352.29	264.42
SG05-01			351.05	1.00	351.05	263.92	351.70	264.1	263.92	351.67	263.95
SG05-02			351.20	1.00	351.20	263.94	351.71	264.10	264.02	351.72	263.98
SG05-03			351.13	0.99	351.12	263.94	351.71	264.10	264.02	351.72	263.98
SG05-04			351.40	1.00	351.40	263.94	351.71	264.10	264.02	351.72	263.98
SG06-01			351.47	1.33	351.44	264.14	351.84	264.05	264.18	351.87	264.11
SG06-02			351.57	1.33	351.57	264.20	351.94	264.10	264.24	351.91	264.14
SG06-03			351.40	1.33	351.39	264.20	351.94	264.10	264.24	351.91	264.14
SG06-04			351.33	1.33	1.33	264.01	351.67	263.97	263.96	351.64	264.03
SG07-01	351.11	1.08	351.10			6-9	R-R	B-B	W-W		
SG07-02	351.04	1.08	351.03			0.50	0.51	0.51	0.50		
SG07-03	351.06	1.08	351.05			0.50	0.51	0.51	0.50		
SG07-04	350.93	1.08	350.94			264.10	352.00	264.32	264.16	352.03	264.16
SG08-01	351.76	1.21	351.24			6-9	R-R	B-B	W-W		
SG08-02	351.78	1.20	351.24			0.50	0.49	0.50	0.54		
SG08-03	351.18	1.21	351.17			1-3	262.8	126.351.8	13.9	351.7	
SG08-04	351.45	1.20	351.44			6-9	B-B	W-W			
SG09-01	351.64	1.37	351.62			0.50	0.50	0.50	0.50		
SG09-02	351.34	1.37	351.32			RE	264.7	126.352.7	13.9	352.0	
SG09-03	351.33	1.32	351.32			2-3	57-12	58-13	W-W		
SG09-04	351.23	1.37	351.21			0.49	0.49	0.49	0.49		
SG10-01	351.27	1.26	351.21			264.04	351.8	264.04	264.13	351.80	264.17
SG10-02	352.00	1.26	351.94								
SG10-03	351.60	1.24	351.67								
SG10-04	352.30	1.26	352.47								
SG11-01											
SG11-02											
SG11-03											
SG11-04											
SG12-01						264.14	351.84	264.18	263.44	351.82	264.20
SG12-02											
SG12-03											
SG12-04											
SG13-01						264.14	352.01	264.44	264.24	352.01	264.21
SG13-02											
SG13-03											
SG13-04											
SG14-01						264.40	352.14	264.15	264.15	352.13	264.13
SG14-02											
SG14-03											
SG14-04											

Seco-1#
Post FORM 1

12/16/20
A. SIMMS

12/28/20
A. SIMMS
@ Splice
TO BLADE

Figure S32. Pre-deployment strain gage checkout sheet—full-bridge checkout. Note: this project spanned multiple months and multiple checklists were necessary. Photo by Andrew Simms / NREL.

Verdant TP Blades Post Deployment Strain Gage Checkout							By: A. Simms	Date: 11/2/21
	Red - White (Ex + to S-) Nominal: ~262 Ω	Red - Black (Ex + to Ex -) Nominal: ~350 Ω	Red - Green (Ex + to S +) Nominal: ~262 Ω	White-Black (S - to Ex -) Nominal: ~262 Ω	White - Green (S - to S +) Nominal: ~350 Ω	Black - Green (Ex - to S +) Nominal: ~262 Ω		
SG 01 - BL1 - FB	(2-3) 264.00	(1-3) 351.57	(3-4) 263.91	(1-2) 263.74	(2-4) 351.57	(1-4) 264.12		
SG 02 - BL1 - FB	(6-8) 264.05	(7-8) 351.74	(5-8) 264.22	(6-7) 263.74	(5-6) 351.71	(5-7) 264.07		
SG 03 - BL1 - FB	(2-3) 264.07	(1-3) 351.77	(3-4) 264.41	(1-2) 264.08	(2-4) 351.98	(1-4) 264.21		
SG 04 - BL1 - FB	(6-8) 264.81	(7-8) 352.61	(5-8) 264.66	(6-7) 264.56	(5-6) 352.49	(5-7) 264.72		
SG 05 - BL1 - FB	(2-3) 263.95	(1-3) 351.69	(3-4) 264.10	(1-2) 264.00	(2-4) 351.70	(1-4) 263.99		
SG 06 - BL1 - FB	(6-8) 264.36	(7-8) 352.09	(5-8) 264.71	(6-7) 264.37	(5-6) 351.97	(5-7) 264.18		
SG 07 - BL2 - FB	(2-3) 264.02	(1-3) 351.62	(3-4) 263.97	(1-2) 263.92	(2-4) 351.61	(1-4) 264.06		
SG 08 - BL2 - FB	(6-8) 264.54	(7-8) 352.08	(5-8) 264.34	(6-7) 264.17	(5-6) 352.05	(5-7) 264.19		
SG 09 - BL2 - HB		(1-3) (700Ω) 702.9	(3-4) (350Ω) 351.88			(1-4) (350Ω) 351.90		
SG 10 - BL2 - HB		(7-8) (700Ω) 704.7	(5-8) (350Ω) 352.96			(5-7) (350Ω) 352.66		
SG 11 - BL3 - FB	(2-3) 264.11	(1-3) 351.73	(3-4) 264.09	(1-2) 264.16	(2-4) 351.91	(1-4) 264.22		
SG 12 - BL3 - FB	(6-8) 264.13	(7-8) 351.80	(5-8) 264.20	(6-7) 263.99	(5-6) 351.77	(5-7) 264.19		
SG 13 - BL3 - FB	(2-3) 264.29	(1-3) 352.07	(3-4) 264.53	(1-2) 264.27	(2-4) 352.06	(1-4) 264.27		
SG 14 - BL3 - FB	(6-8) 264.56	(7-8) 352.27	(5-8) 264.27	(6-7) 264.67	(5-6) 352.25	(5-7) 264.50		
	Red - White	White - Black	Red - Black					
SG15 - BL3 - OB	(3-4) 353.77	(1-4) 3.68	(1-3) 353.77					
SG16 - BL3 - OB	(5-8) OPEN	(5-7) OPEN	(7-8) OPEN					

MCIL8M Blade Side Connector Face View

Figure S33. Strain gage resistance checkout sheet, post-deployment. Note: 15 out of 16 gages reported nominal values. Photo by Andrew Simms / NREL.