# COMPOSITE SANDWICH REPAIR USING THROUGH-THICKNESS REINFORCEMENT WITH ROBOTIC HAND MICRO-DRILLING

*M. Suresh, A. Sanders, P. Prajapati, K.Kaipa, O. G. Kravchenko*
*Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, VA*

## Abstract

The novel through-thickness reinforcement and repair method of composite sandwich structures is proposed. The method allows for restoring the load-carrying capacity of composite sandwich structures with delamination and disbond type of damage. The high level of reconfigurability of the present TTR technique was achieved by incorporating the robotic hand micro-drilling setup, which uses a force-controlled process with safe human-robot collaboration features. The present study showed the potential way for reinforcing of pristine composite sandwich, as well as, damaged (delaminated/disbonded) structures, allowing to restore the load-carrying capacity of completely failed sandwiches. The developed TTR repair technique was investigated using 4-point bending configuration. The effectiveness of the method was shown to strongly depend on the aspect ratio of the embedded TTR carbon fiber pin.

## INTRODUCTION

Composite materials, due to their low density and excellent mechanical properties, are ideal material for weight savings for structural applications [1]. Carbon fiber composites and carbon fiber sandwich panels are widely used, specifically in the aerospace and automotive industry due to the superior structural properties they offer. Failure modes of composites vary from surface failure of the ply, delamination in the composite face sheet, disbond between the face sheet and core material, to name a few. Typically, fiber or matrix breakage results in delamination cracks that upon reaching critical size can cause catastrophic failure (Figure 1). A better understanding of how to suppress delamination propagation is needed to prevent structural failure of composites.

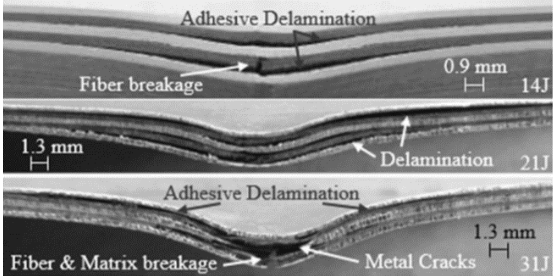


*Figure 1. Interlaminar damage in composites [2]*

Through-thickness reinforcement (TTR) technique is typically used to improve delamination resistance for the structure. One typical TTR approach is to use z-pinning technique to reduce the delamination by incorporation of carbon fiber pins into the prepreg [4]. As Childress et al. mention, the z-pinning of composite structures provides a 35% increase in compression after impact strength and could prevent bonded substructure from disbonding when subjected to blast loads [4]. A recently proposed technique to enhance the delamination resistance in composite laminates by TTR is based on embedding pultruded carbon fiber composite rods of small diameters (0.51mm), which are oriented orthogonally to the plane of the post-cured laminate. This method uses cured laminates unlike the case of Z pinning which uses prepregs [6]. A schematic of TTR is shown below in Figure 2. The length to diameter ratio is known as the aspect ratio of the rod. Kravchenko et al. experimentally showed [5] that an increased aspect ratio of through-thickness rods significantly elevates mode I maximum delamination fracture resistance of composite laminates.

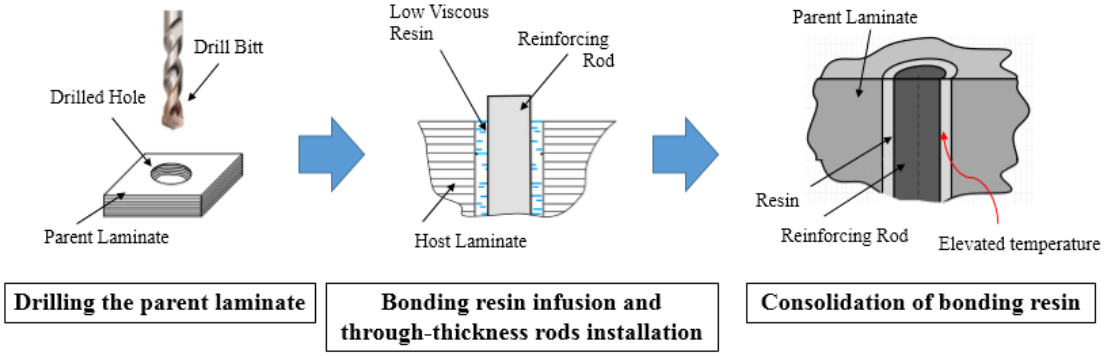


*Figure 2. Schematic of TTR on cured composite laminate [6]*

The present work introduced the use of TTR of cured laminates to reinforce and repair the composite sandwich structures (Figure 3). The repair required micro-drilling operation, which was conducted by a robotic hand micro-drilling setup, with force control capability, that was developed in-house [19]. Optimal force conditions for micro-drilling were determined to avoid microdrill failure. The present study focused on understanding of how TTR can be used to promote damage tolerance in composite sandwich structures with delamination and disbond defects. The methodology is based on 4- point bending testing of the fabricated carbon fiber sandwich panels with embedded delamination or disbond cracks. The effectiveness of TTR is studied using the pristine, reinforced and repaired sandwiches. In the case of repaired samples they were first mechanically tested until failure, which developed in the face sheet laminate. Laminate failure occurred due to buckling of the disjointed plies on the compressive side of the panel. Then, the TTR technique was used to repair the samples, which upon testing, revealed complete recovery of the load carrying capacity. Digital image correlation was used to get a better understanding of the crack propagation and different failure modes in pristine and repaired composite sandwiches. Therefore, the proposed TTR repair was found to be effective in promoting damage tolerance in sandwich structures, while robotic hand implementation allows for a reconfigurable and an automated repair technique.

a. b.

*Figure 3. Robotic hand micro-drilling setup [19]*

## MATERIALS USED

Composite carbon fiber sandwiches consist of the face sheets and the sandwich core in between them (Figure 4). The face sheets are generally thin layers relative to the core material that vary in thickness. A thin adhesive layer is used between the face sheet and the honeycomb core, which enables better bonding [7], [8]. The core materials can also vary depending on the desired stiffness and strength properties. The material for the core can include polymeric [9,10] or hybrid foams, pyramidal lattice cores [11], aluminum [12,13], and aramid honeycomb cores. The latter material was used in the present work due to its wide applicability for structural applications.

In the present study we used carbon fiber woven laminates manufactured using wet layup process. The face sheets consisted of four layers of plane weave and the core material was Nomex honeycomb, which consists of aramid fibers with phenolic resin [14]. The scope of the work considered flexural behavior of sandwich beams loaded in quasi-static configuration, while future work can consider impact testing [15] of sandwich panels, which is known to produce substantial delamination damage. A metal base tool is used during fabrication, while the release film was used to avoid adhesion of the plate after the curing process to the tool plate. The epoxy resin used for the wet layup process was INF 114 (Part A) and INF 211 (Part B) Fusion Resin. Parts A and B were mixed in the ratio of 3:1 respectively. A few layers of breather material were used on the top surface of the sandwich layup, on the bag side. Breather material provided the necessary air pathway for removing the trapped air during the layup process. The specimen was covered in a vacuum bag and sealed. Prior to curing process the composite was debulked for 20 min and placed into hot press. The importance of heat treatment while curing is extremely important. Heat treatment and pressure affect the curing process and improving the specimen strength and properties [16] indicating a toughening of the filled resin matrix and an improved filler/matrix adhesion [17]. Cure cycle for samples consisted of two isothermal stages. Stage one of the curing in the heat press was at 176$^{o}$F at 20 psi pressure for 2 hours. Stage two used the temperature of 265ºF with a pressure of 80psi for additional 2 hours. Once the plate was cured, the rectangular specimens were fabricated using the water jet. Pultruded unidirectional carbon rods of 0.019” (0.48mm) thickness were used for the through thickness reinforcement repair of the sandwich.

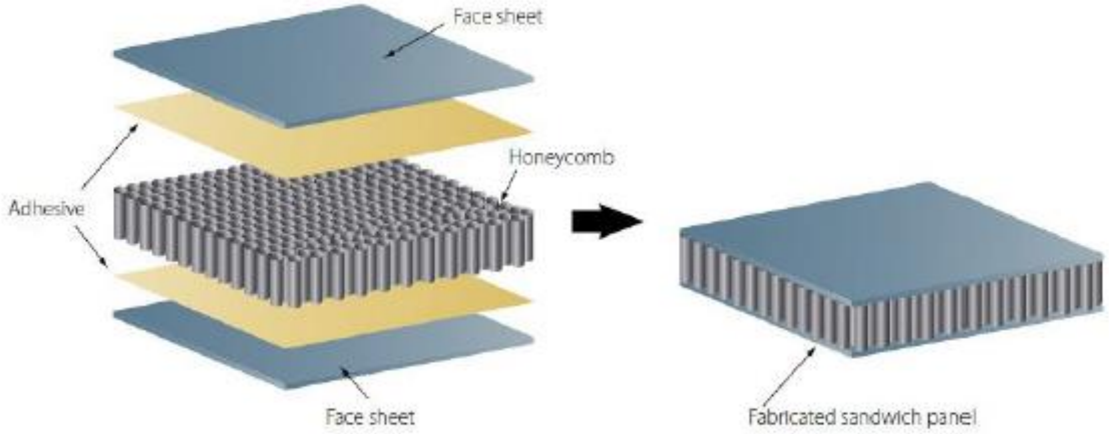


*Figure 4. Composite sandwich structure configuration*

## METHODS

To suppress crack propagation, through-thickness reinforcement (TTR) is used by installing them into the face-sheet laminate using micro-drilling operation. The efficiency of TTR in suppressing the delamination or disbond crack growth was evaluated by considering the sample configurations with embedded delamination and disbond cracks using polytetrafluoroethylene, Teflon, film inserts. Teflon inserts were used on the top side of the sandwich panel, that was subjected to compressive loading during testing, in the mid-span location. The disbond crack was created by embedding the film insert between the core and the top face sheet, while delamination crack was created between 2nd and 3rd ply. The width of both defects was 1”. Furthermore, the effectiveness of TTR repair under combined crack propagation and face sheet failure of the sandwich beams with the presence of adhesive layer is considered, which provides a case of strong face-sheet/core interface. Stiffness and strength of the samples are then compared and indicated high effectiveness of TTR in suppressing the crack propagation and restoring structural load carrying capacity in composites.

### *Robotic Micro-Drilling Operation*

Micro-hole drilling (holes 0.5 mm or less in diameter) is gaining increased attention in a wide spectrum of precision production industries [20]. A Sawyer robot from Rethink Robotics, which offers capabilities of safe physical interaction with a human co-worker, kinesthetic teaching, and force control, was used as the test bed [19]. The robot’s end-effector was equipped with a Dremel drill fit into a housing, which was custom designed (Fig. 3b). The force controlled micro-drilling was performed using 5N, which was found to be optimal for the speed of drilling and longevity of the drill bit. The proposed approach applies human-robot collaboration in the following context. A human kinesthetically teaches an initial drilling coordinate by physically holding the robot and guiding it to the required locations (Fib. 3a). Then operator uses the created software code to specify the spacing between the center-to-center coordinates of holes, which were 5 mm in the present study.The robot executes the drilling task by moving to these locations. Thereby this avoids the need to specify the drill coordinates with respect to a fixed reference frame, leading to reduction in programming effort and setup time while transitioning between different drilling jobs.

### *Installation of TTR rods*

The fabricated specimen, used for studying the TTR effectiveness, were covered with Teflon tape before the TTR repair in order to avoid the adhesion of excess resin on the upper surface of the face-sheet and the sides of the sandwich beam (Figure 5), which can interfere with the experimental results by affecting the stiffness of the specimen after the repair. The low viscosity vacuum infusion resin was used to infiltrate the created array of holes with resin, following the manual installation of the rods.

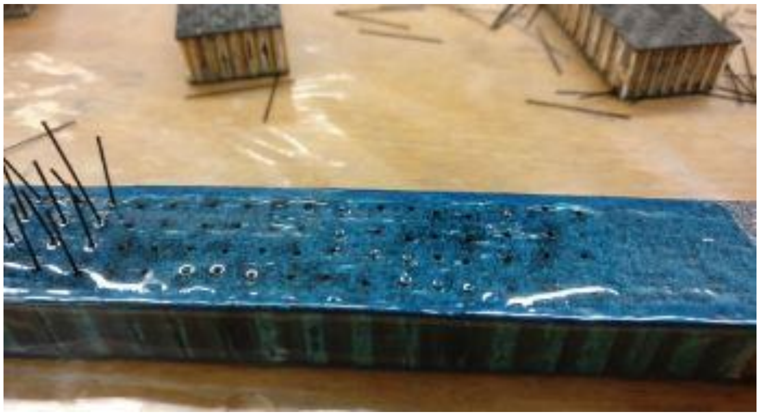


*Figure 5. TTR Repair and taping of specimen during TTR Repair*

The post curing of samples with TTR was conducted at ambient room temperature, after which the tape is removed and the surface was polished. DinoLite Digital Microscope was used to understand the rod alignment inside the cells of honeycomb structure (Figure 6). As can be seen in Fig. 6, the fibrous rods penetrated inside the honeycomb cell. Some of the cells were partially filled with the infused resin, that allowed bonding between the pins, face sheet laminate and the cell walls itself. It is expected that the increased embedded length of the TTR inside of the laminate and cell walls positively affects the overall efficiency of the TTR technique, due to the higher effective aspect ratio of the reinforcing pin.

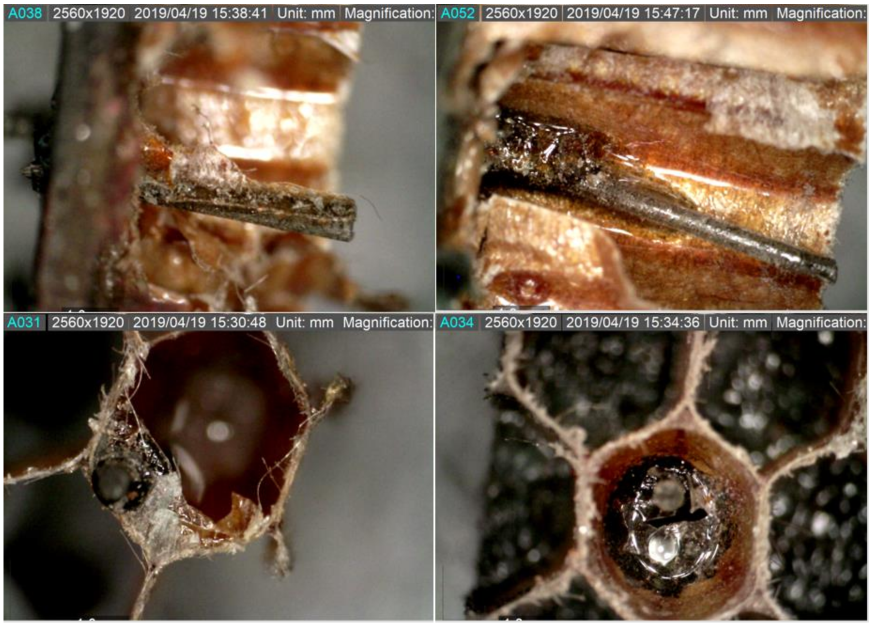


*Figure 6. Microscope images showing cured resin and carbon rod alignment inside the honeycomb structure*

### Four-Point Bending Testing of Composite Sandwich

The samples were 21” in length with a width of 1” with the core thickness of 0.48”. The overall average height was 0.52”. The samples were subjected to a 4- point bending test with the upper supports being 3” apart. (Figure 7). The schematics with the TTR pattern and the actual sample during testing are shown in Fig. 7. Digital Image Correlation (DIC) was used [18] to record the full field strain profiles and to capture the progression of failure during the test.

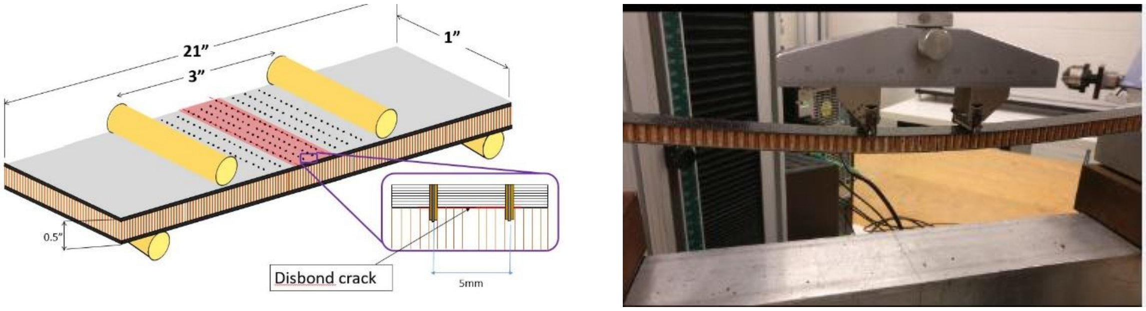


*Figure 7. Sandwich beam under 4 Point Bending Setup*

## EXPERIMENTAL RESULTS

### Flexural Behavior of Composite Sandwich without TTR

Figure 8 shows the comparison of characteristic load-displacement curves for the pristine, delaminated and disbonded samples without TTR. As expected, the pristine samples have the highest load at failure, while the delaminated samples and disbonded samples exhibit about 55% and 35% of the critical load for pristine sample, respectively.

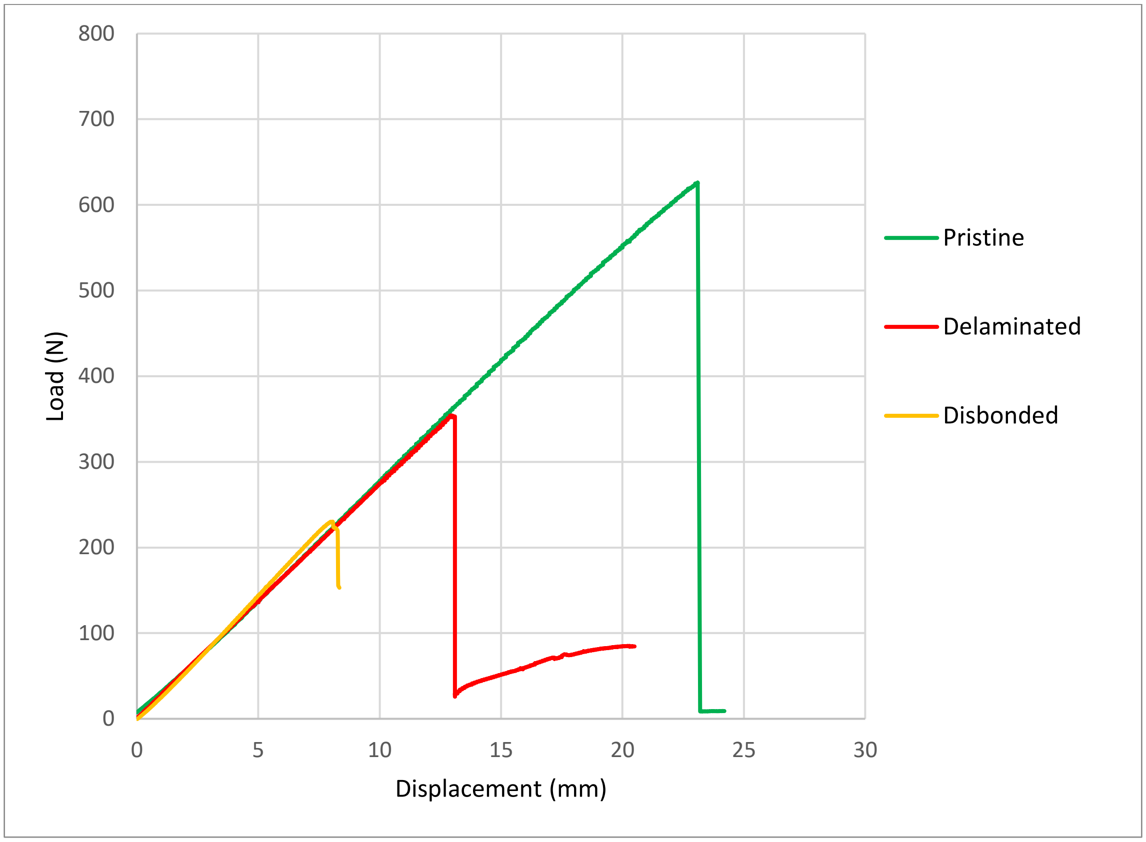


*Figure 8. Characteristic Load vs Displacement curve for samples without TTR*

The linear region of the load-displacement for the disbonded sample showed planar deformation on the top surface of the face sheet laminate (Fig. 9a), however, upon reaching near the critical load buckling initiated in the disjointed laminate (Fig. 9b), followed by face sheet laminate failure due to the excessive bending (Fig. 9c), at which point the significant drop in the load occurred. Interesting to point out that the disbond crack did not propagate further, therefore the rest of laminate remained bonded to the core due to the strong interface between honeycomb and face sheet, created by the adhesive film. The delaminated specimen showed failure of the face sheet laminate in the midspan location as well. The honeycomb core remained unaffected in both disbonded and delaminated sample unlike in testing of the pristine samples. The load-displacement of the pristine sample indicates instantaneous failure followed by the load drop. The failure occurred due to face sheet failure with minor core crush, but the interface between the face sheet and core remained intact (Fig. 9d).

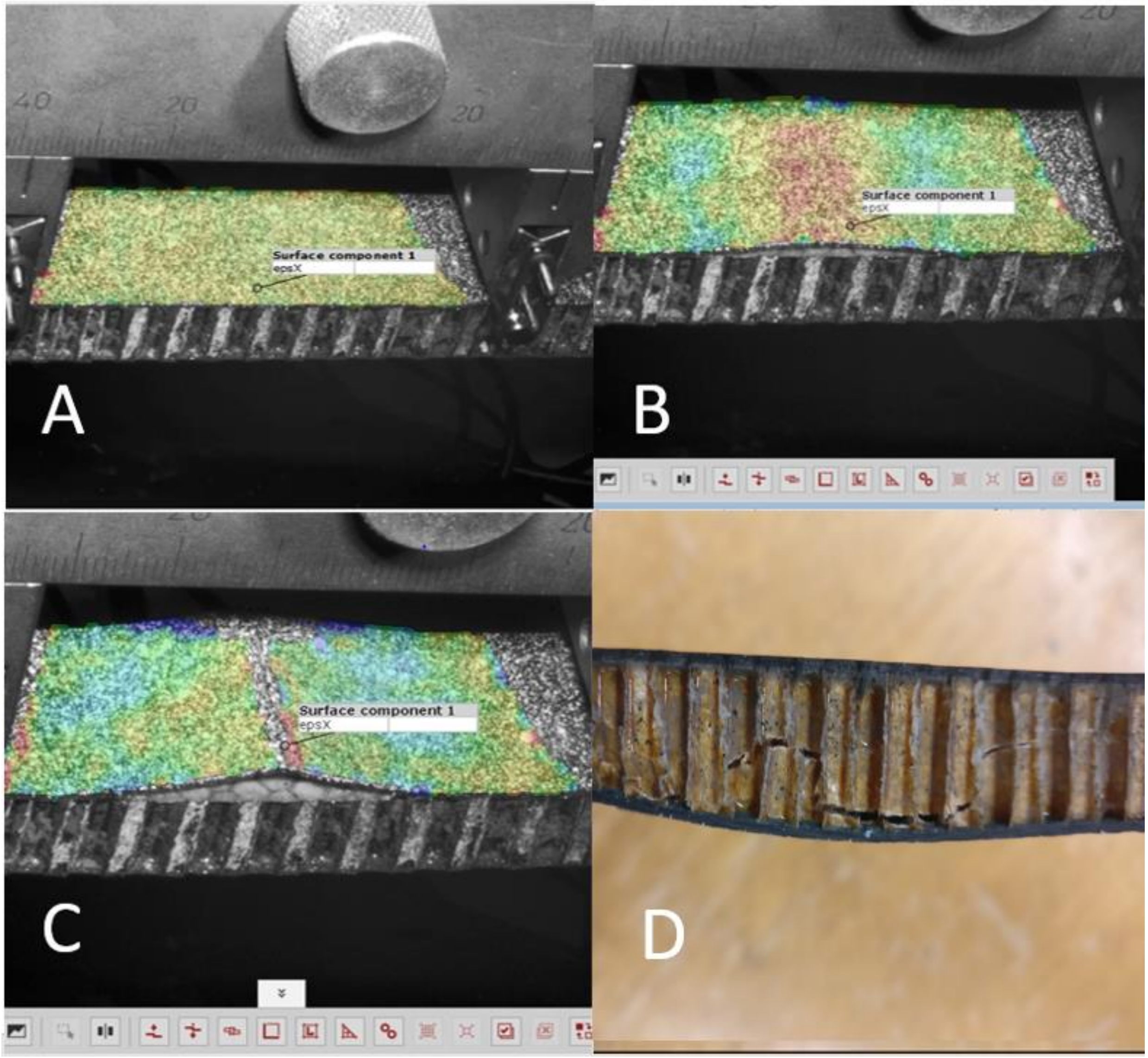


*Figure 9 a) DIC image at initial loading of disbonded specimen without TTR. b) Face sheet buckling initiation just above the disbond. c) surface failure observed due to increased face-sheet core bonding at interface d) core damage in the pristine specimen upon failure.*

Figure 10 shows the average strength of different groups of samples and their standard deviation. The average failure load is the highest for pristine specimen and lowest for the specimen with the embedded disbond.

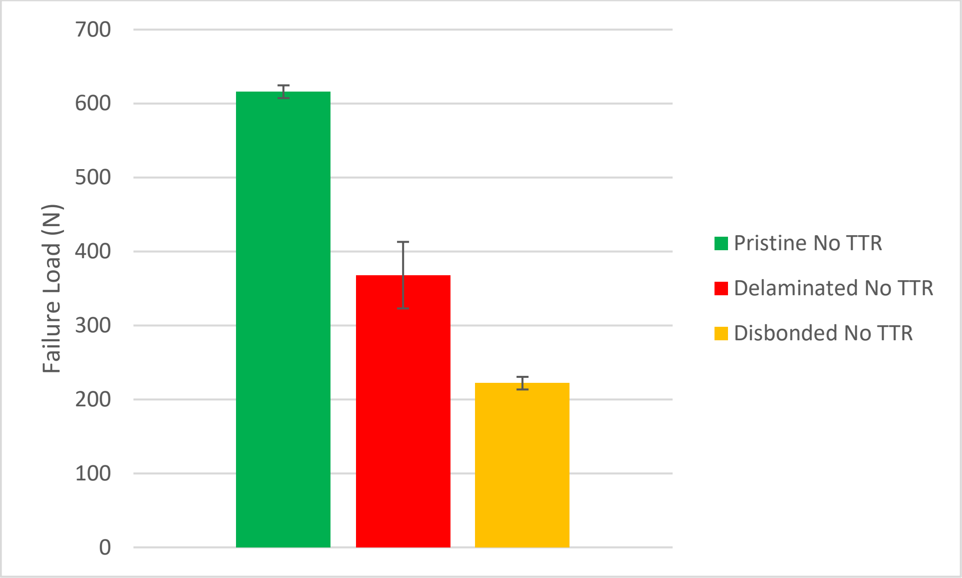


*Figure 10. Failure load for composite sandwich beams in pristine configuration and with embedded defects*

### ***Flexural Behavior of Composite Sandwich with TTR Repair***

The study was focused on delamination suppression and the effectiveness of TTR in restoring the strength of the delaminated and disbonded specimen. Therefore, the repair was not carried out on pristine samples in this study, which showed failed due in the core region, without developing delamination during testing. The pultruded carbon pins were inserted into the 3” region centrally located between the top pins for both the disbonded and delaminated specimen. The spacing between the rows of TTR was 5 mm. The crack that developed through the thickness of the face sheet laminate was approximately 2.5 mm from the closest row of TTR on both sides of the specimen. Once samples were repaired, they were subjected to another flexural test. The delaminated samples upon TTR repair (Fig. 11), showed rod pull-out of the top half of face sheet laminate. The pull-out of the rods initiated in the row, which was closest to the laminate crack and quickly propagated causing failure in the sample. The disbonded specimen after TTR (Fig.12), exhibited similar TTR pull-out failure as in the case of the delaminated specimen, however, in certain cases the localized core crush near the midspan location was observed.The interface between core and face sheet was intact at failure as seen in Figure 11-12 below.

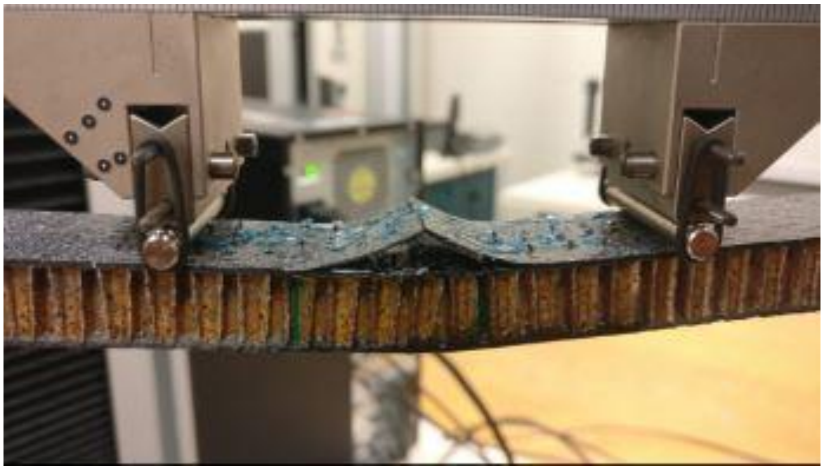


*Figure 11. Surface buckling and failure of delaminated specimen after TTR repair*

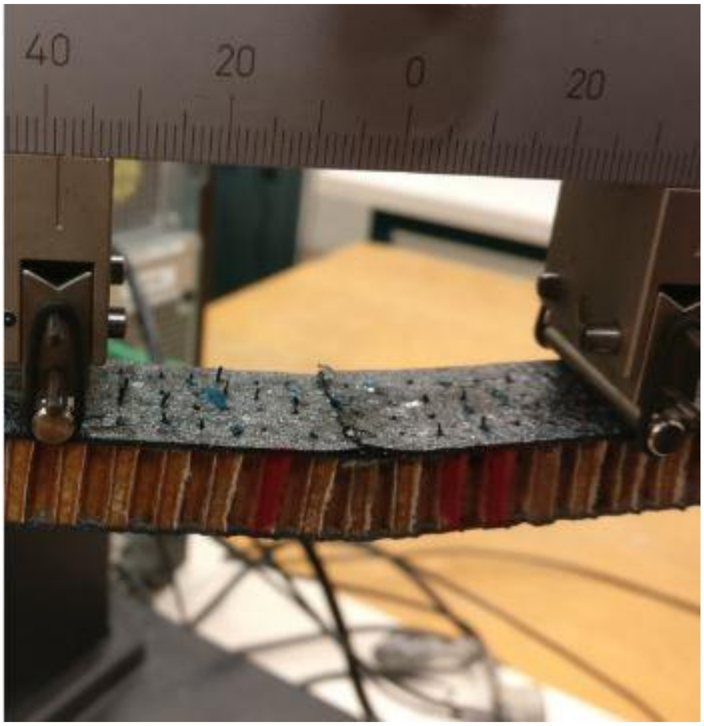


*Figure 12. Surface failure below upper roller and damage to core in disbonded specimen after TTR repair*

Figure 13 shows the characteristic load-displacement curves for the TTR repaired specimen in comparison to the specimen without TTR. Both groups of repaired samples indicate that critical load can be substantially improved due to the presence of TTR (Fig. 13). Fig. 14 shows the average critical load and standard deviation for two groups of the repaired samples. The results indicate that the critical load for the samples with TTR repair is greater for the disbonded samples, then compared to delaminaited samples. Prior to TTR repair, disbonded samples showed significantly lower critical load than samples with delamination (recall Fig. 10). This result signifies the role of the aspect ratio of the embedded TTR length, which is larger in the disbonded sample. It is also worth noticing that the stiffness remains almost the same throughout all the specimen with and without the TTR repair, which is due primarily to the fact that disbond or delamination mostly remain closed during the initial linear part of the load-displacement curve.

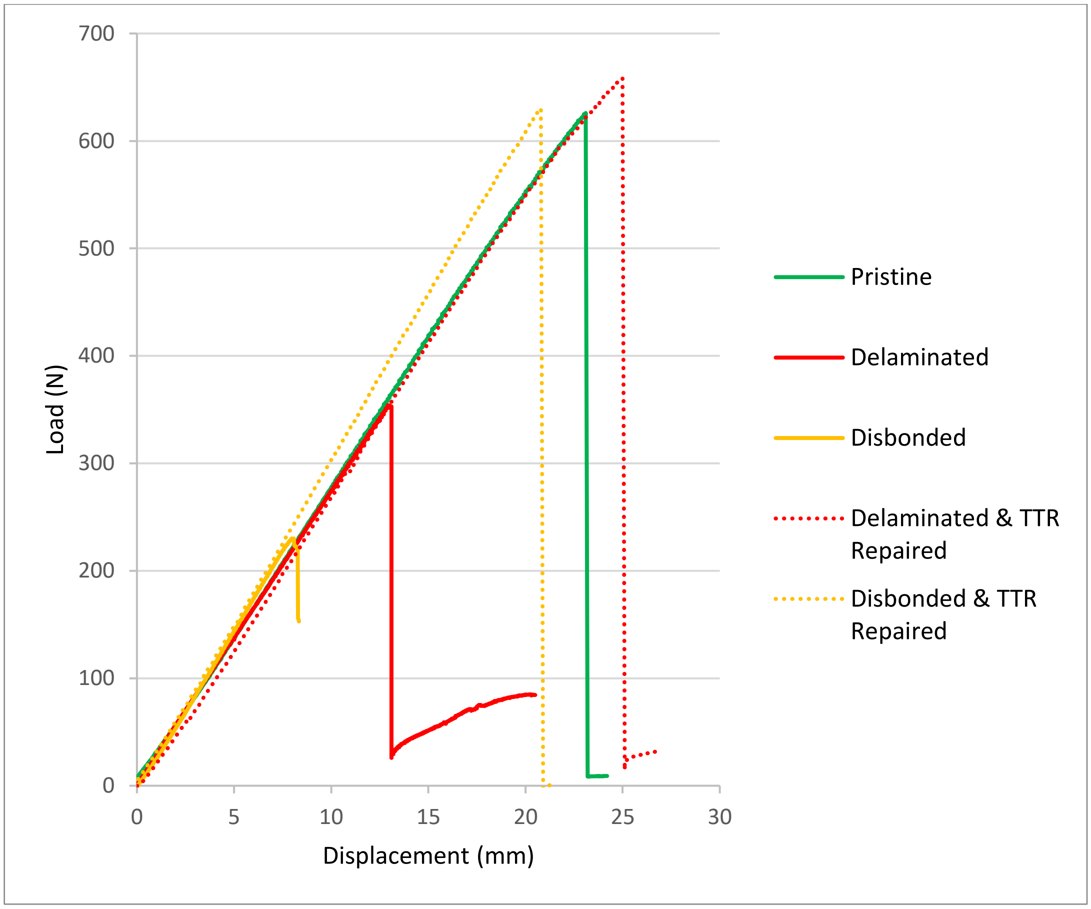


*Figure 13.Characteristic load-displacement curve for TTR repaired specimen*

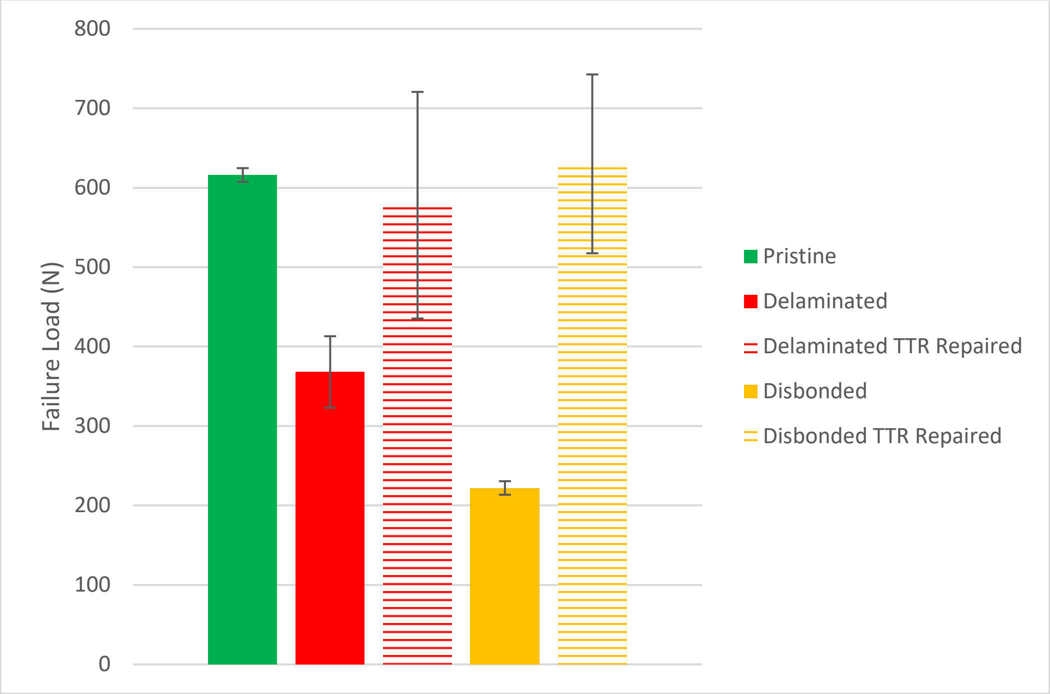
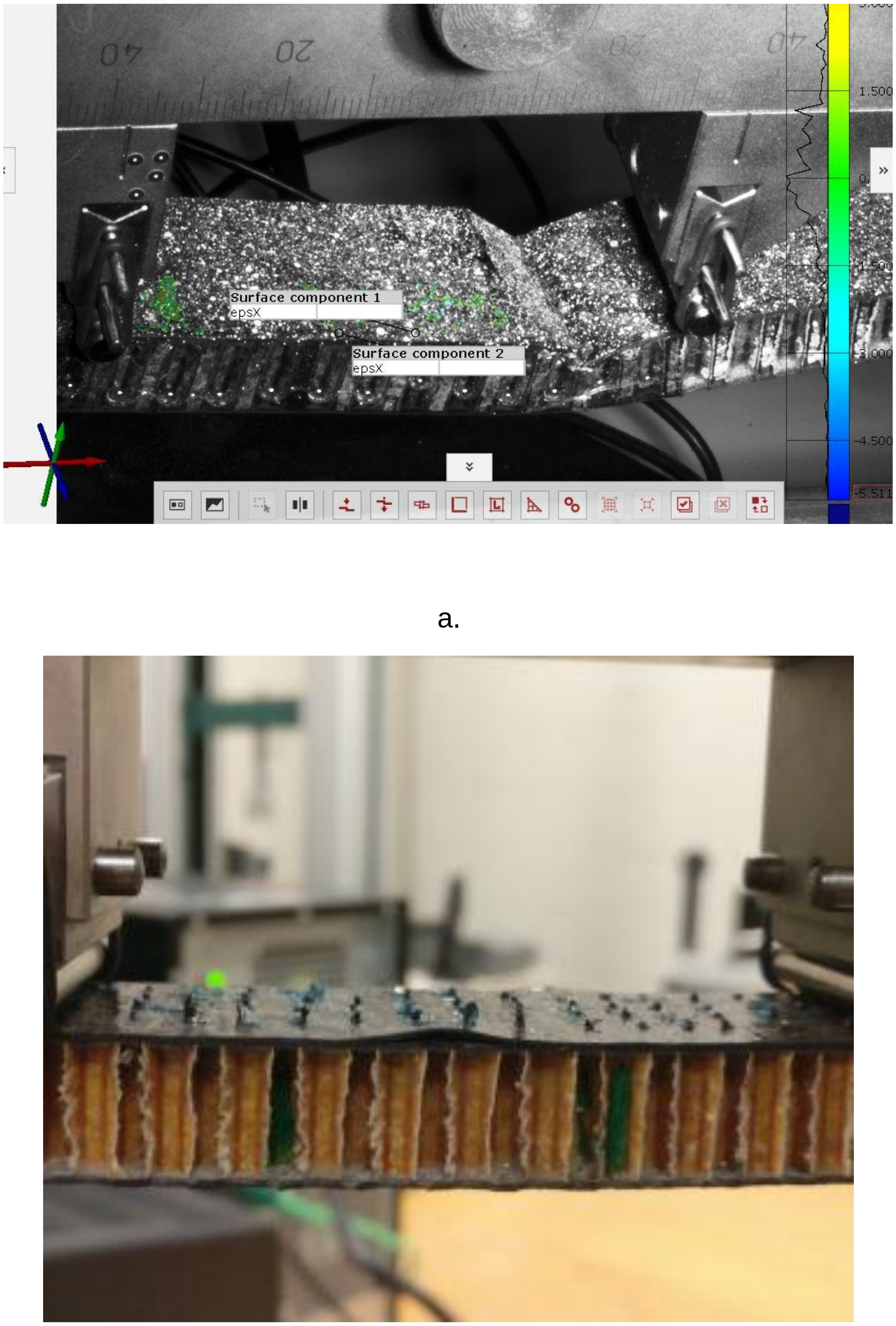


*Figure 14. Effect of TTR repair on composite sandwiches*

### *Flexural Behavior of Composite Sandwich with TTR Reinforcement*

TTR reinforcement was conducted to understand the effect of the present technique to enhance the strength of pristine configuration, as well as, its effect on untested delaminated and disbonded specimens. The pristine specimen exhibited similar failure compared to the failure in pristine samples without TTR. The failure occurred due to face sheet failure with minor core crush and crack is observed in the honeycomb core but the interface between the face sheet and honeycomb core remained intact (recall Fig. 9d). The failure for the disbonded specimen was instantaneous, and along with face sheet failure it exhibited honeycomb core crushing near one of the loading top pins, while the honeycomb core and face sheet interface remained bonded (Fig. 15a). Some delaminated specimen experienced minor buckling of the upper surface in the face sheet, but it was arrested because of the presence of the TTR reinforcement as seen in Figure 15b before surface failure occurred.



a.

b.

*Figure 15: a. DIC image of the failure in TTR reinforced disbonded specimen; b. delamination of top layers over the TTR reinforced region in the TTR reinforced delaminated specimen just before surface failure*

Figure 16 shows the characteristic load-displacement curves for the TTR reinforced specimen in comparison to the specimen without TTR. The load at failure of the delaminated and the disbonded specimen are similar to the pristine specimen failure loads, which shows that the TTR reinforcement increases the load carrying capacity of the disbonded and delaminated specimen to near the pristine strength. It is noticed that the stiffness remains almost the same throughout all the specimen with and without the TTR reinforcement, which is similar to the samples with TTR repair. Fig. 17 shows the average and standard deviation for the samples with TTR reinforcement. The important observation is that the strength of the TTR reinforced pristine sample is marginally higher than the strength of the pristine, which can be explained by the load redistribution due to the presence of the TTR that resulted in more extensive damage progression in TTR reinforced sample, than compared to pristine. Also, similar trend is observed for TTR reinforced samples, in which the effectiveness of the TTR reinforcement for the disbonded sample was higher than in delaminated sample.

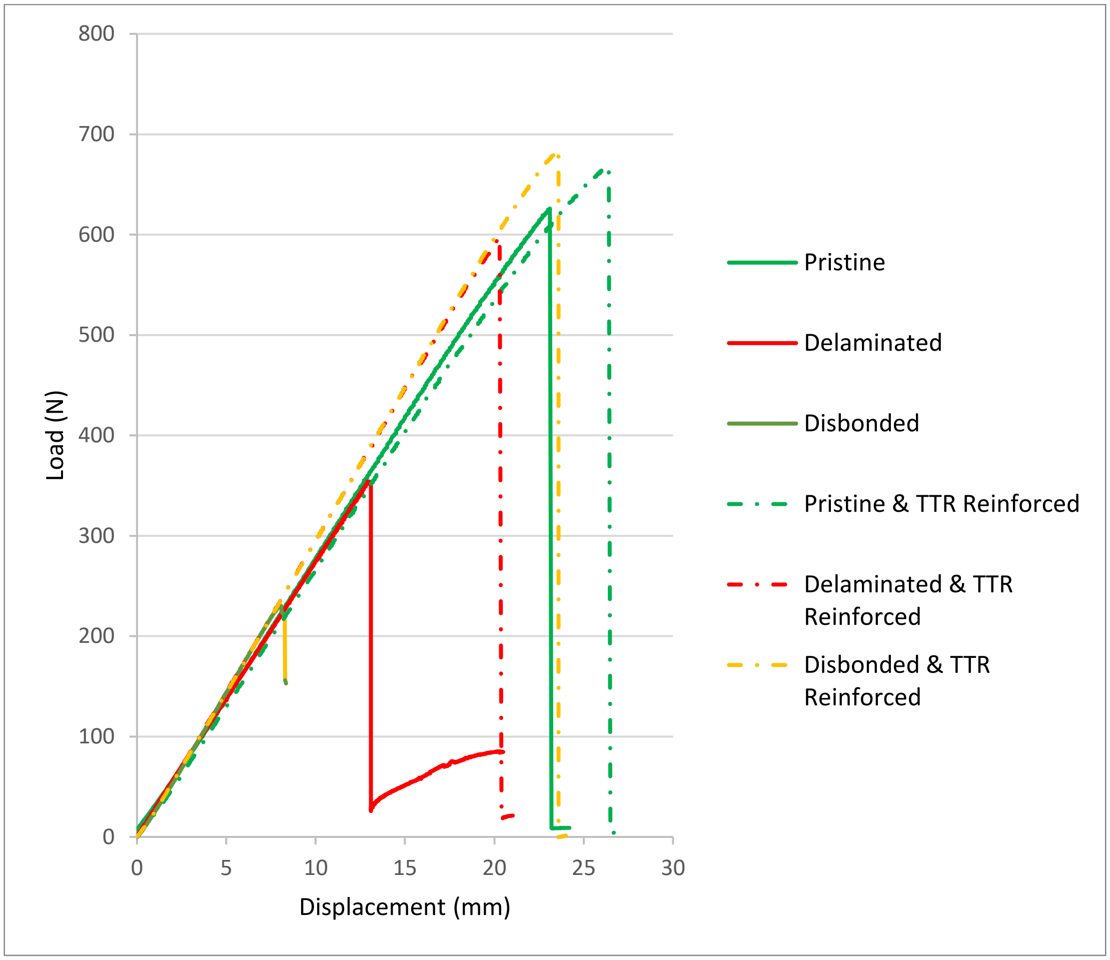


*Figure 16. Characteristic Load vs Displacement curve for TTR Reinforced specimen*

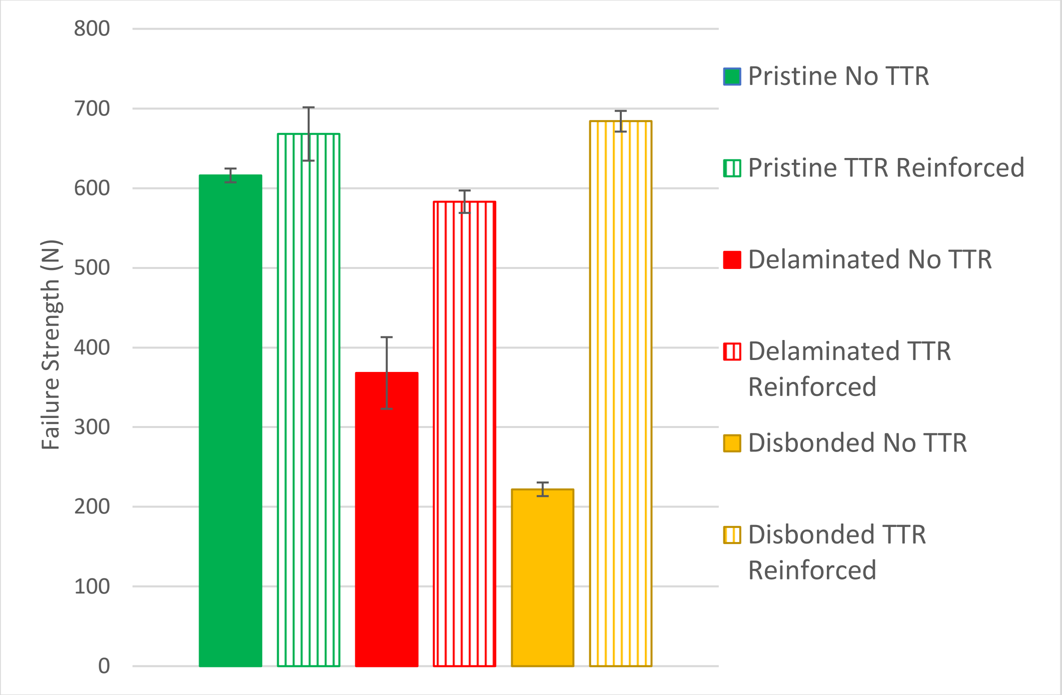


*Figure 17. Effect of TTR reinforcement on composite sandwiches*

## CONCLUSION

The load-carrying capability of failed composite sandwich with substantial delamination or disbond damage, which results in laminate face sheet failure, was restored using TTR technique based on insertion of submillimeter fibrous pins in the failed face sheet and the honeycomb cells. The bonding between pin and the honeycomb/laminate was achieved by using low viscosity epoxy resin. The strength of the repaired sandwich beams was restored and matched the strength of pristine sandwich samples. The TTR reinforcement also showed the ability to enhance the strength of the samples with the induced defects without failed face sheet laminate, while also providing a marginal increase in the strength of pristine samples. The overall effectiveness of the repair was found to be dependent on aspect ratio (AR), defined by the embedded pin length to the diameter. The higher aspect ratio allows for more effective shear stress transfer between the TTR pin and laminate that resulted in more effective TTR repair/reinforcement in disbonded samples, when compared to samples with delamination, with lower aspect ratio of TTR. The proposed robotic hand micro-drilling offered efficient way to perform force-controlled drilling of composite laminates. The adopted framework for robotic micro-drilling can be applied to non-flat sandwich panel configuration, allowing for greater reconfigurability of the present TTR technique.

## ACKNOWLEDGEMENTS

The Authors would like to acknowledge The Jeffress Trust Award in Interdisciplinary Research, the Thomas F. and Kate Miller Jeffress Memorial Trust.

# BIBLIOGRAPHY

1. Windhorst, Torsten, and Gordon Blount. "Carbon-carbon composites: a summary of recent developments and applications." Materials & Design 18, no. 1 (1997): 11-15.
2. Gurpinder S. Dhaliwal, Golam M. Newaz. “Modeling Low Velocity Impact Response of Carbon Fiber Reinforced Aluminum Laminates (CARALL)”
3. Ming He and Brian N. Cox. “Crack bridging by through-thickness reinforcement in delaminating curved structures.”
4. J.J Childress and G.A Freitas. “Z- direction pinning of composite laminates for increased survivability.” 1992 Aerospace Design Conference February 3-6, 1992 /Irvine, CA
5. S. G. Kravchenko, O. G. Kravchenko, L. A. Carlsson, R. B. Pipes, “Influence of Through-Thickness Reinforcement Aspect Ratio on Mode I Delamination Fracture Resistance,” Composite Structures, Vol. 125, pp. 13-22, 2015.
6. Sergii Kravchenko, Oleksandr Kravchenko, Mathias Wortmann, Martin Pietrek, Peter Horst, R Byron Pipes. “Composite toughness enhancement with interlaminar reinforcement.” Composites Part A: Applied Science and Manufacturing, Volume 54, November 2013, Pages 98-106.
7. Cantwell WJ, Davies P. A test technique for assessing core-skin adhesion in composite sandwich structures. J Mater Sci Lett 1994;13(3):203–5.
8. An Ural, Alan T. Zehnder, Anthony R. Ingraffea.“Fracture mechanics approach to face-sheet delamination in honeycomb: measurement of energy release rate of the adhesive bond.”
9. Prasad S, Carlsson LA. Debonding and crack kinking in foam core sandwich beams-II. Experimental investigation. Eng Fract Mech 1994;47(6):825–41.
10. Zachary T Kier and Anthony M Waas. “Determining effective interface fracture properties of 3D fiber reinforced foam core sandwich structures”
11. Burak Kiyak and Mete O Kaman. “Mechanical properties of new-manufactured sandwich composite having carbon fiber core”.
12. Mehmet Ziya Okur, Serkan Kangal, Metin Tanoğlu. “Development of Aluminum Honeycomb Cored Carbon Fiber Reinforced Polymer Composite Based Sandwich Structure”.
13. S Dinesh, T Rajasekaran, M Dhanasekaran, K Vigneshwaran. “Experimental testing on mechanical properties of sandwich structured carbon fibers reinforced composites” in 2nd International conference on Advances in Mechanical Engineering (ICAME 2018). IOP Conf. Series: Materials Science and Engineering 402 (2018) 012180 doi:10.1088/1757-899X/402/1/012180.
14. Garam Kim, Tyler Futch, Ronald Sterkenburg, Sadat Ahsan, Gozdem Kilaz, Brian Kozak Purdue University. “Investigating The Effects of Fluid Intrusion on Nomex Honeycomb Structures with Carbon Fiber Face Sheets”. Proceedings of the 2017 Conference for Industry and Education Collaboration, American Society for Engineering Education.
15. Fan Xia and Xiao Qing Wu. “Work on Impact Properties of Foam Sandwich Composites with Different Structure”. Key Laboratory for Advanced Textile Composite of Ministry of Education, Tianjin Polytechnic University, Tianjin 300160, China.
16. Shinkai K, Suzuki S, Leinfelder KF, Katoh Y. “How heat treatment and thermal cycling affect

wear of composite resin inlays.” Department of Operative Dentistry, Nippon Dental University, School of Dentistry, Niigata, Japan.

17. Ferracane JL, Condon JR. “Post-cure heat treatments for composites: properties and fractography.” Department of Dental Materials Science, Oregon Health Sciences University, Portland.
18. Available at https://www.gom.com/metrology-systems/aramis.html.
19. P. Prajapathi, “Human-robot collaborative force-controlled micro-drilling for advanced manufacturing and medical applications”, *Masters Thesis,* Department of Mechanical and Aerospace Engineering, Old Dominion University, December 2018.
20. Cheong, Man Sheel, Dong-Woo Cho, and Kornel F. Ehmann. "Identification and control for micro-drilling productivity enhancement." International Journal of Machine Tools and Manufacture 39, no. 10 (1999): 1539-1561.