Efficiency of Hybrid Fastening System with Varying Bolt Diameters

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Introduction / Relevance - Joining

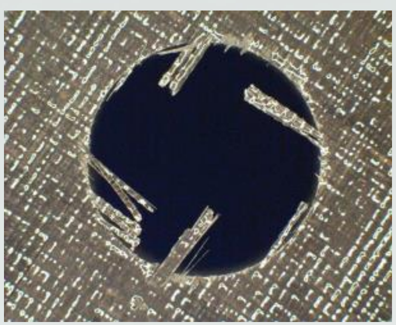
- **JOINING / ASSEMBLY:**

– Joining is inevitable, allows versatility in assembly and repair, reduces costs and time.

– Considered a 'weak-link' in the structure due to complex phenomena & interactions.

Mechanical Fastening

- **PROS: a) Repair and Re-assembly, b) confidence in use as it is commonly used**
- **CONS : a) Adds Weight, b) machining holes, c) delamination in composites, d) stress-concentrations**



Delamination in composites due to hole-drilling, Gardiner, Composites World , (2012)

Adhesive Bonding

- **PROS: a) Light Weight and b) load distribution over larger areas**
- **CONS : a) permanent joint (cannot be repaired or re-assembled), b) lack of confidence in common use to reliability of bonding.**

Examples of Adhesive Joints
a) Lap-Joint , b) Double Lap-Joint

There is a Need for a JOINING TECHNIQUE that can INHERIT the MERITS of BOTH bolted & bonded techniques and still being compatible with current assembly line practices

Fastener research is complicated by the large number of parameters involved

- Thickness
- Fastener type (bolt, rivet…)
- Mixture of materials
- Hybrid joinings
- Preload clamping
- Fastener size and scaling effects
- Tapered threads
- Clearance and interference fits
- Washers (flat, spring, conical)
- Material properties
- Hole shape
- Hole treatment
- Inserts and bushings
- Fastener arrays
- Edge distance

- Fastener shape
- Torque (shear) effect on composite
- Clamping load relaxation
- Manufacturing issues
- Blind fasteners (one-side access)
- Impact, blast, stress and shock waves
- Validation especially important for fastenings

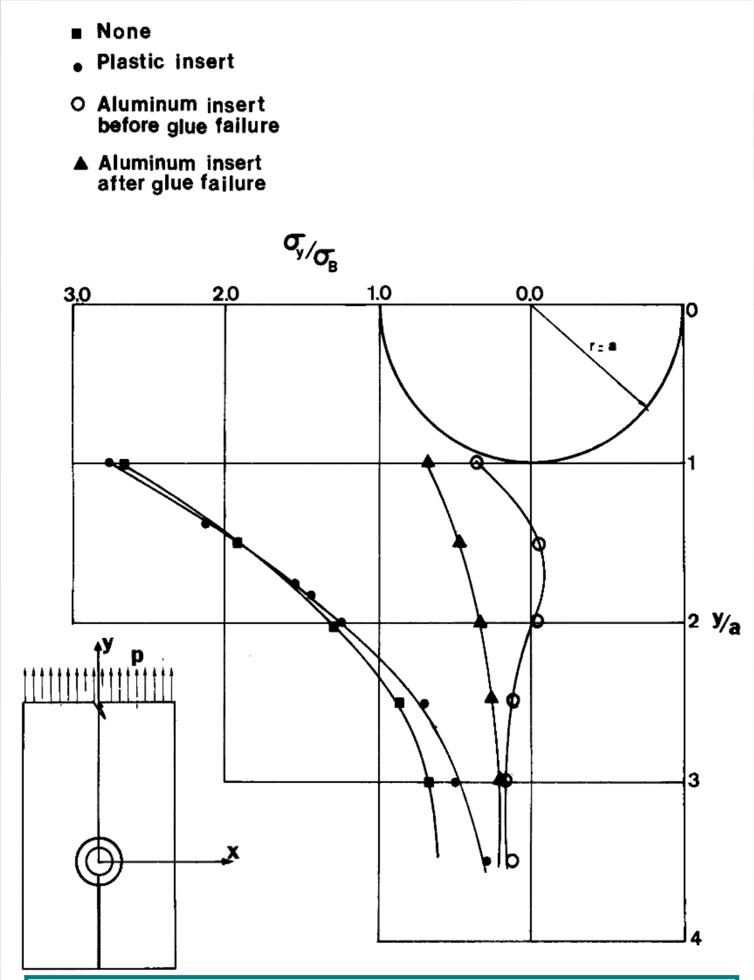
This list is not complete!

- **Now, for multi-material joining, these parameters get more complicated.**
- **FRP composites add to additional parameters:**
  - Delamination
  - Laminate stack-up
  - Environmental factors, creep, etc.,
  - Main Limitation with FRP Composites: <u>Additional Structural Weight due to fasteners</u> and <u>drilling holes/stress-concentrations / delaminations</u>.

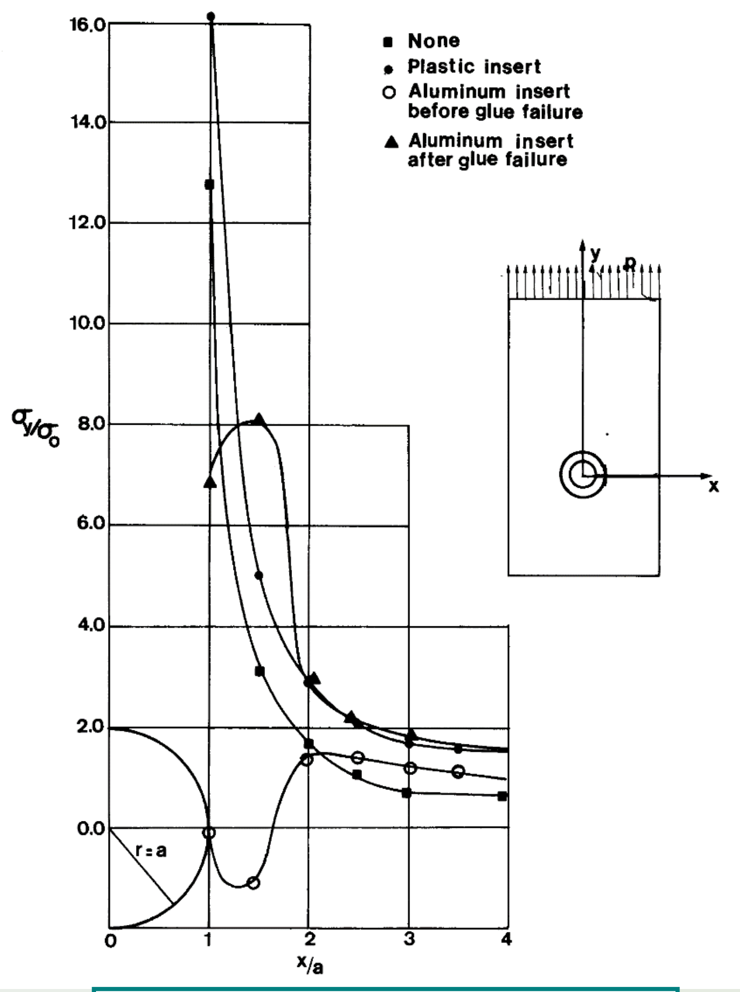
Source: Cloud G. (2013) Experimental Mechanics, 53 (7) 1073-1104

MOTIVATION: Inserts

Stress concentrations in Fasteners: with and without inserts



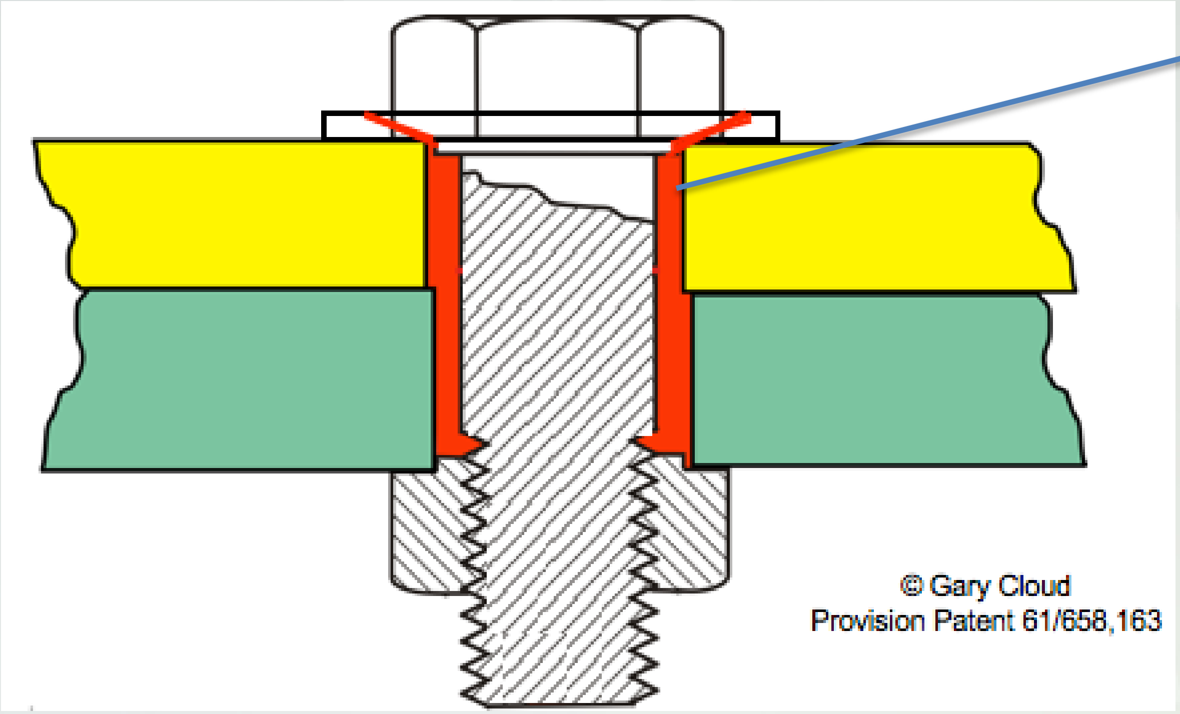
Bearing stress concentration factors for orthotropic specimens with inserts of various materials



Ligament stress concentration factors for orthotropic specimens with inserts of various materials

SOLUTION: Hybrid Bolted Joints
An Overview

The basic concept of injected hybrid fastener
"adhesive structural insert"



Bolt clearance filled by "adhesive structural insert"

Benefits of Hybrid Joints

A few selective benefits of inserts in general and in particular for hybrid (adhesive structural inserts) are provided below.

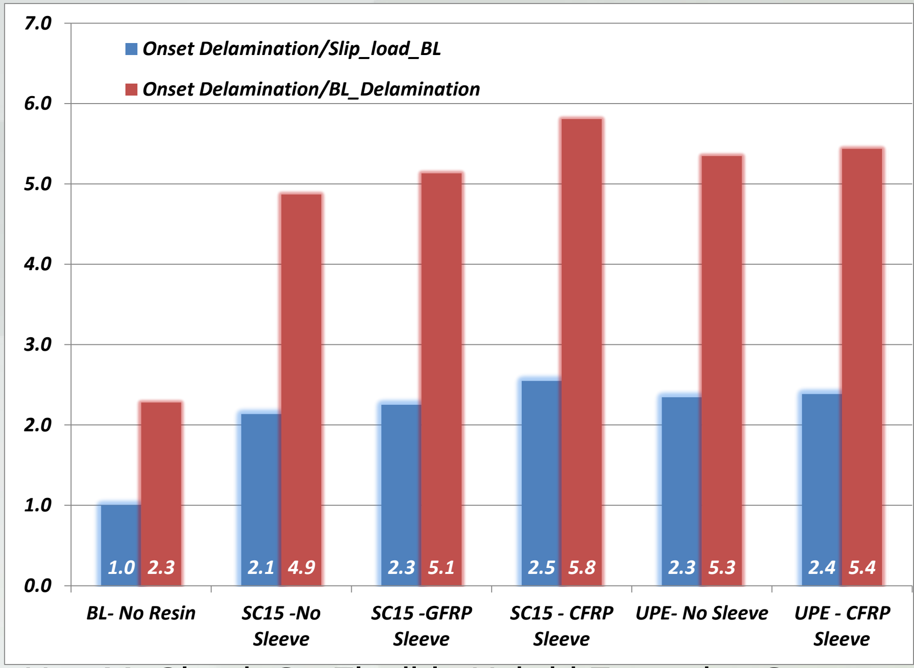
- Improved strength, control of stress concentrations
- Ease of installation
- Field assembly / dis-assembly
- Inexpensive
- Handling of hole misalignment and crude drilling practice
- Elimination/delayed Onset of slip
- Enhanced joint stiffness
- Compatibility with existing industrial practices
- Probably increased fatigue and impact performance (research in progress)

Source: Cloud G. (2013) Experimental Mechanics, 53 (7) 1073-1104

Novelty of this work

Prior work in our research group:

- Similar joints: GFRP to GFRP
- Constant hole ϕ : 0.5" (12.5 mm)
- Hybrid joints were found to be 200% to 500% better than conventional joints



Haq M, Cloud, G., Flexible Hybrid Fastening System. Society of Experimental Mechanics, 2013

In this work

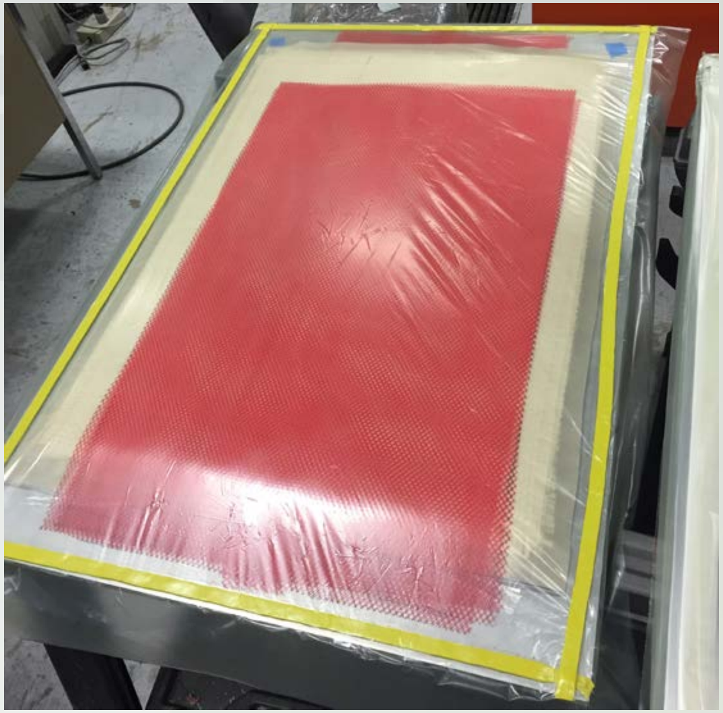
- Dissimilar joints: Aluminum to Carbon
- Varying hole ϕ : 0.25" (6.35 mm) to 0.75" (19.05 mm)

Experimental Plan

- Material:
  - **Substrates:** a) 16 layer plain-weave Biaxial S-Glass/Epoxy, and b) Aluminum 6061
  - **Bolt:** Medium Strength Grade 5 steel right hand hex head bolts
  - **Structural Insert:** SC15 Epoxy (room temperature cured for 24h)
- Experimental response:
  - Tensile -Shear behavior of the joint
  - Failure mode
- Factors Considered:
  - Preload
  - Insert
  - Bolt Diameter

Manufacturing

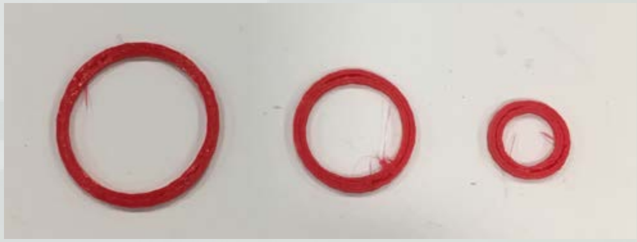
- GFRP plates consisted of 16 layers of biaxial glass fibers
- SC-15 resin was infused using vacuum assisted resin transfer molding (VARTM) process
  - Cure cycle: 2 hours at 60°C followed by 4 hours at 90 °C
- Resulting thickness of the cured plate was 3/8", identical to the aluminum substrates
- Final plates were then cut into proper size using a waterjet



TOP: Typical VARTM setup for GFRP substrate manufactiring

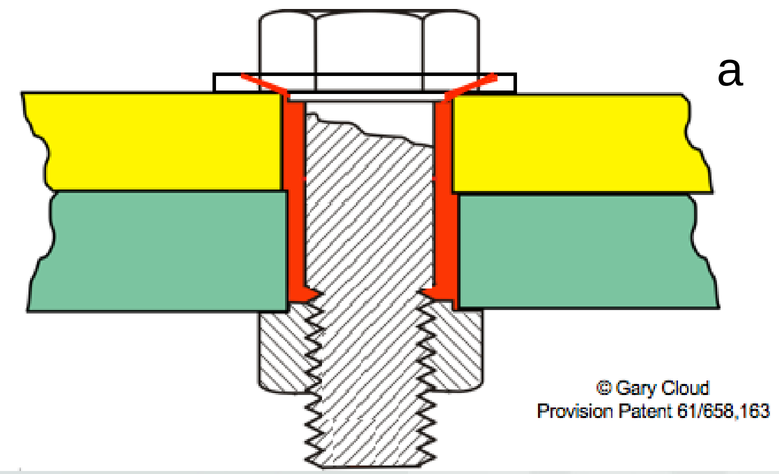
Joint Assembly

- In an effort to center the bolt within the drilled hole of the GFRP and Aluminum substrates, centering discs were attached to the washers
- Discs were 3d printed-PLA (poly lactic acid) filament and attached to washer using super glue (cyanoacrylate)
- Outside diameter of disc was set to be the same as hole diameter and inside diameter the same as bolt diameter.
- Joints were preloaded to 70% of bolt yield strength

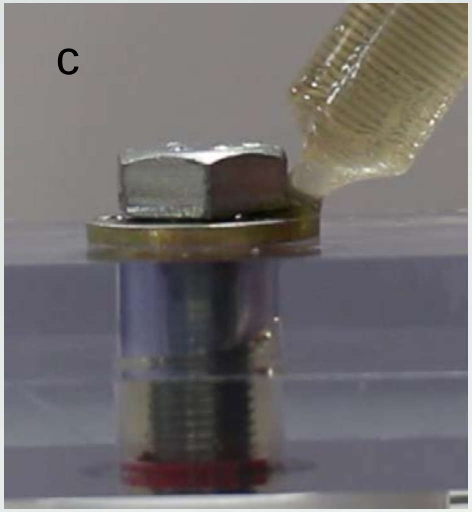


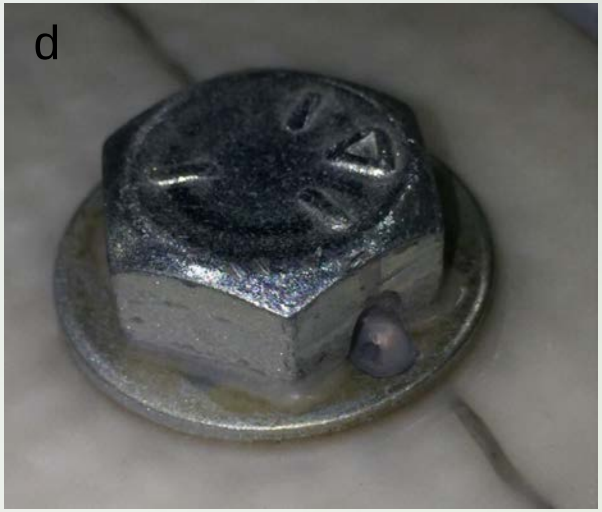
TOP: bolt-centering in the hole using 3D printed low strength rings attached to washers
LEFT: transparent polycarbonate joint showing joint assembly

Hybrid Bolted Joints: Structural Adhesive Insert



(a) Schematic of hybrid joint, (b) notches on washer to introduce the adhesive insert, (c) joint assembly in transparent substrates showing adhesive filling the clearance, (d) completed joint that shows excess resin expelling air and overflowing from the cavity





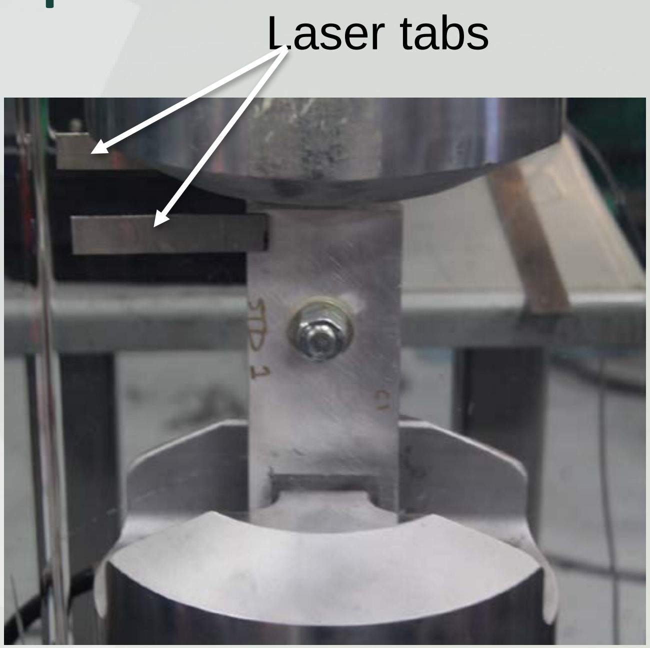
Injection / Placing Structural adhesive insert

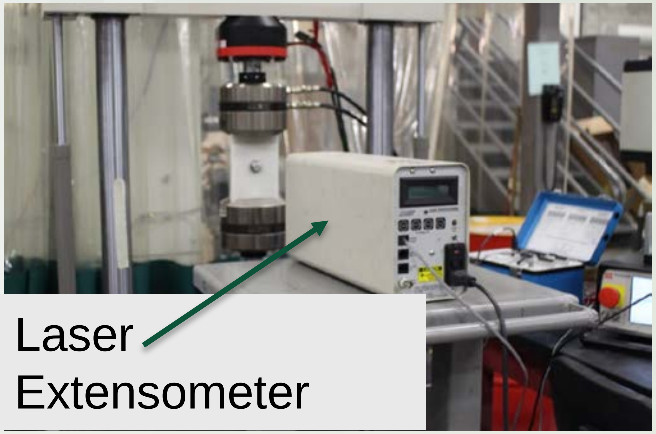
VIDEO CLIP SHOWING ADHESIVE INJECTION PROCESS

Will show as a black box in PDF file

Experimental setup

- The quasi-static experimental test was performed with servo-hydraulic testing machine (MTS 810).
- A testing rate of 10 mm/min was maintained for all joints.
- An external laser extensometer was used to measure the relative substrate displacements





Results

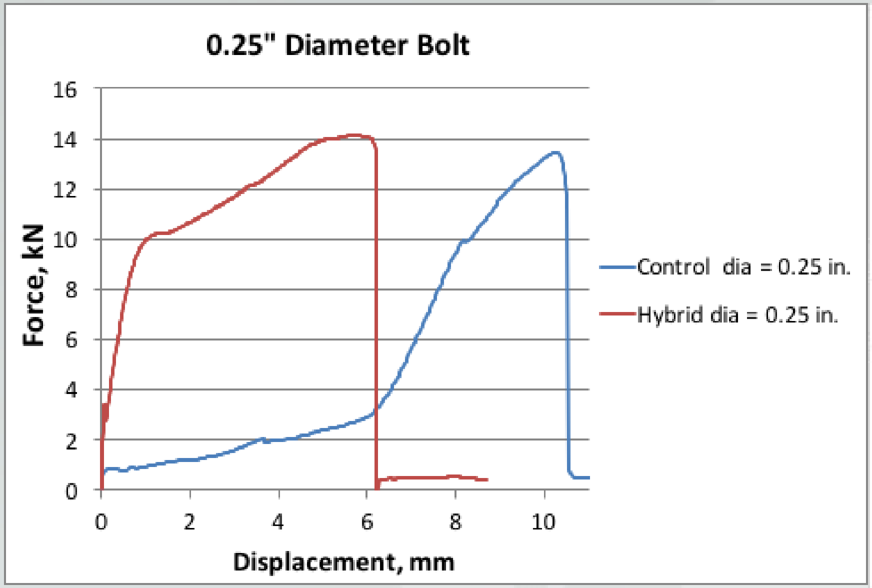
- **Nomenclature:**
  - All controlled or standard joints data is presented as the blue lines on the graph
  - 3 joints per case study were tested

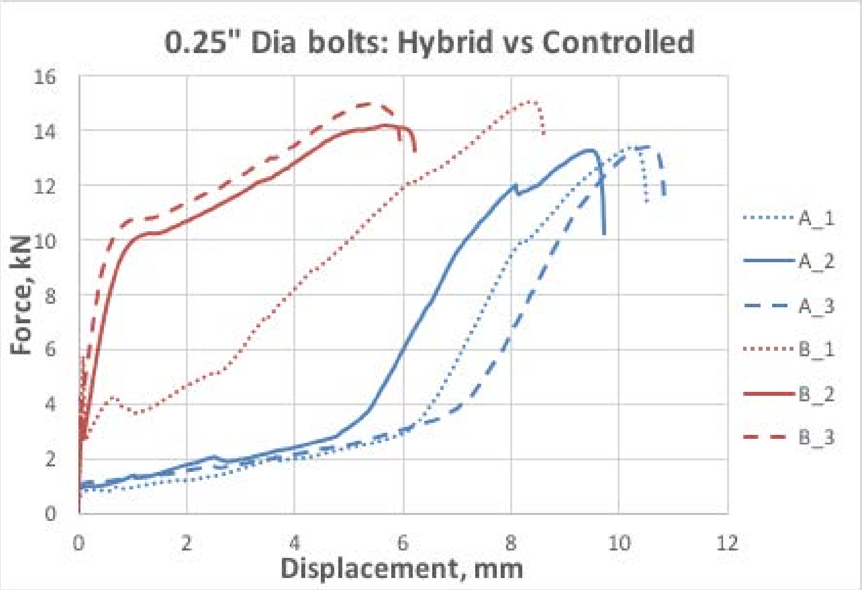
Table: Nomenclature used in this work

Bolt diameter	Conventional / Control Joints	Hybrid Joints
0.25”	A	B
0.50”	C	D
0.75”	E	F

  - Comparison for “A” with “B” plus “C” with “D” and “E” with “F” will give the enhancement due to adhesive structural insert
  - The MTS frame capacity used in this work was 100 kN. Joints with 0.75” diameter were stopped at 80kN for safety concerns

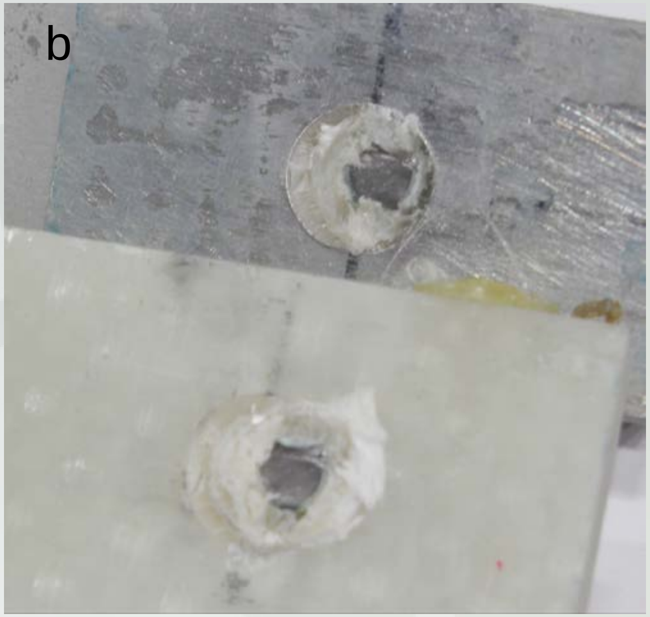
0.25" Diameter bolt – Hybrid vs Control Joints





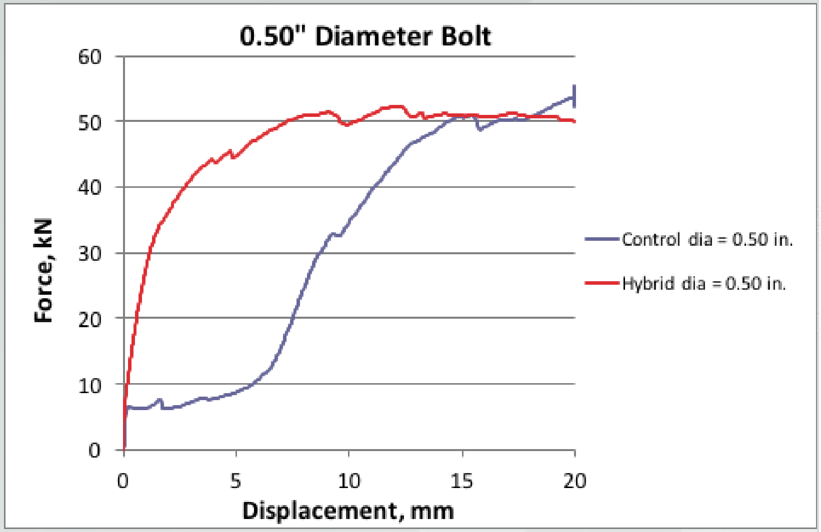
- When the shear forces exceed compressive forces from the bolts holding the substrates, slip occurs in conventional joints. NO SLIP is observed in HYBRID joints, except in poorly filled resin
- If slip is critical, it can be seen that the hybrid joints performed almost 10x better then the standard joints
- Stiffness of the joint has improved significantly through higher loads being applied

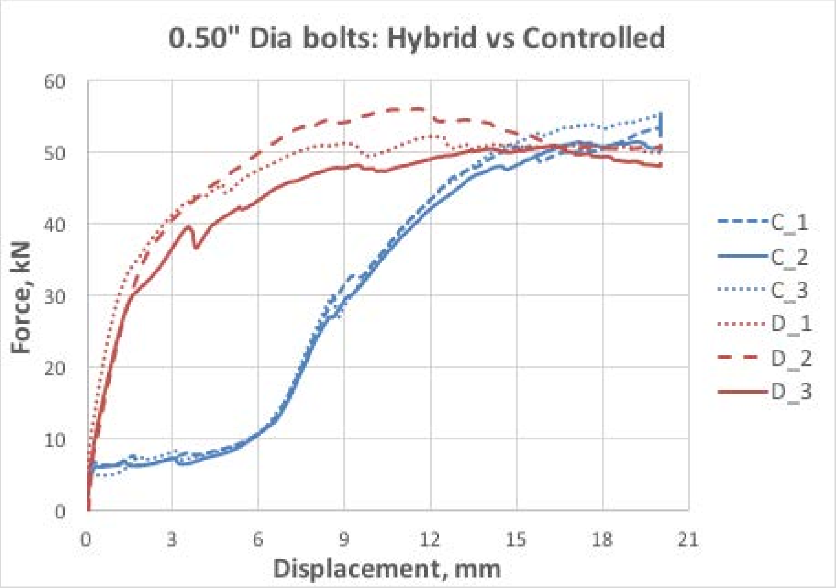
0.25” Failure Mode



a) Bolt shear on a conventional joint
b) Bolt shear with resin infused through the cavity of the hybrid fastener
c) Following the slip, the bolt has sheared on the angle at which it has made contact with the substrate which was consistent with all tests

0.50" Diameter bolt – Hybrid vs Control Joints





- If slip is critical then, it can be seen the hybrid bolts perform approximately 7-8x better than the controlled
- Delamination begins to occur much later than that of the controlled bolt
- Stiffness enhancement is consistent as 0.25" bolted joint

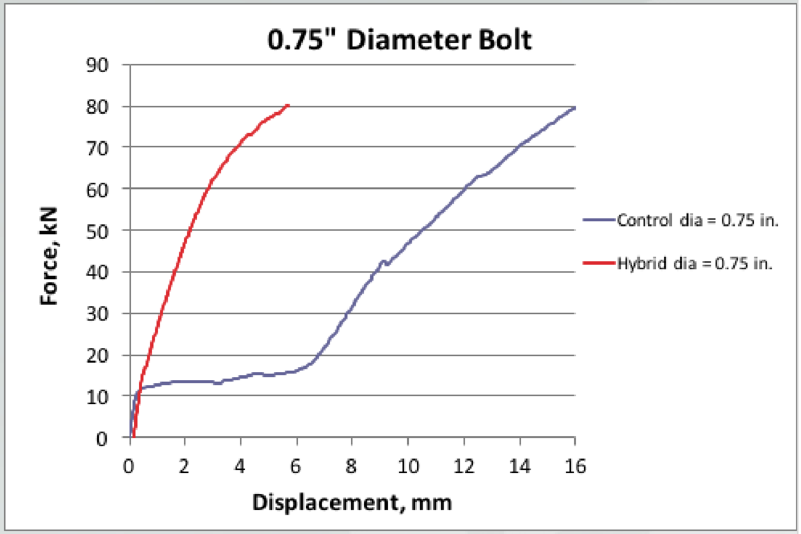
0.50” Diameter bolt – Failure modes

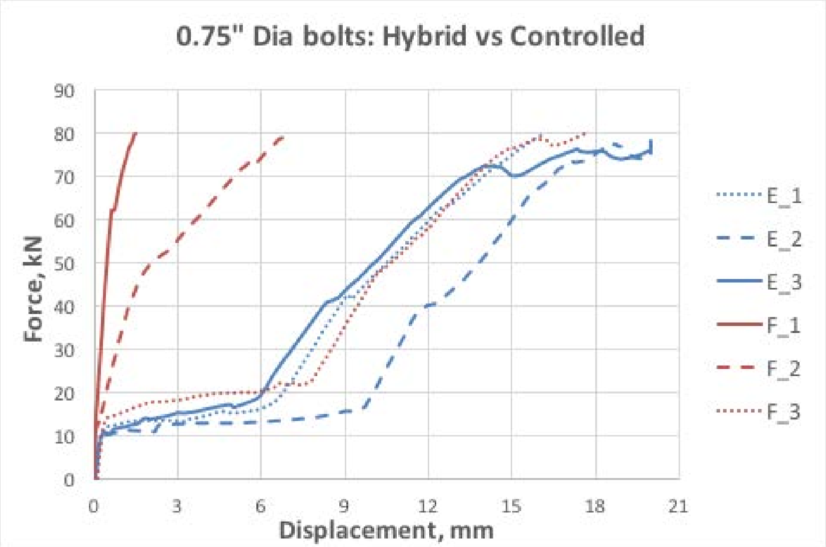
a) Delamination on the standard bolt has extended to the edge of substrate

b) No delamination present on the edge of substrate despite bending in aluminum as well as bolt

c) Standard joint on left shows significantly more damage around bolt hole compared to that of hybrid joint on right from top view

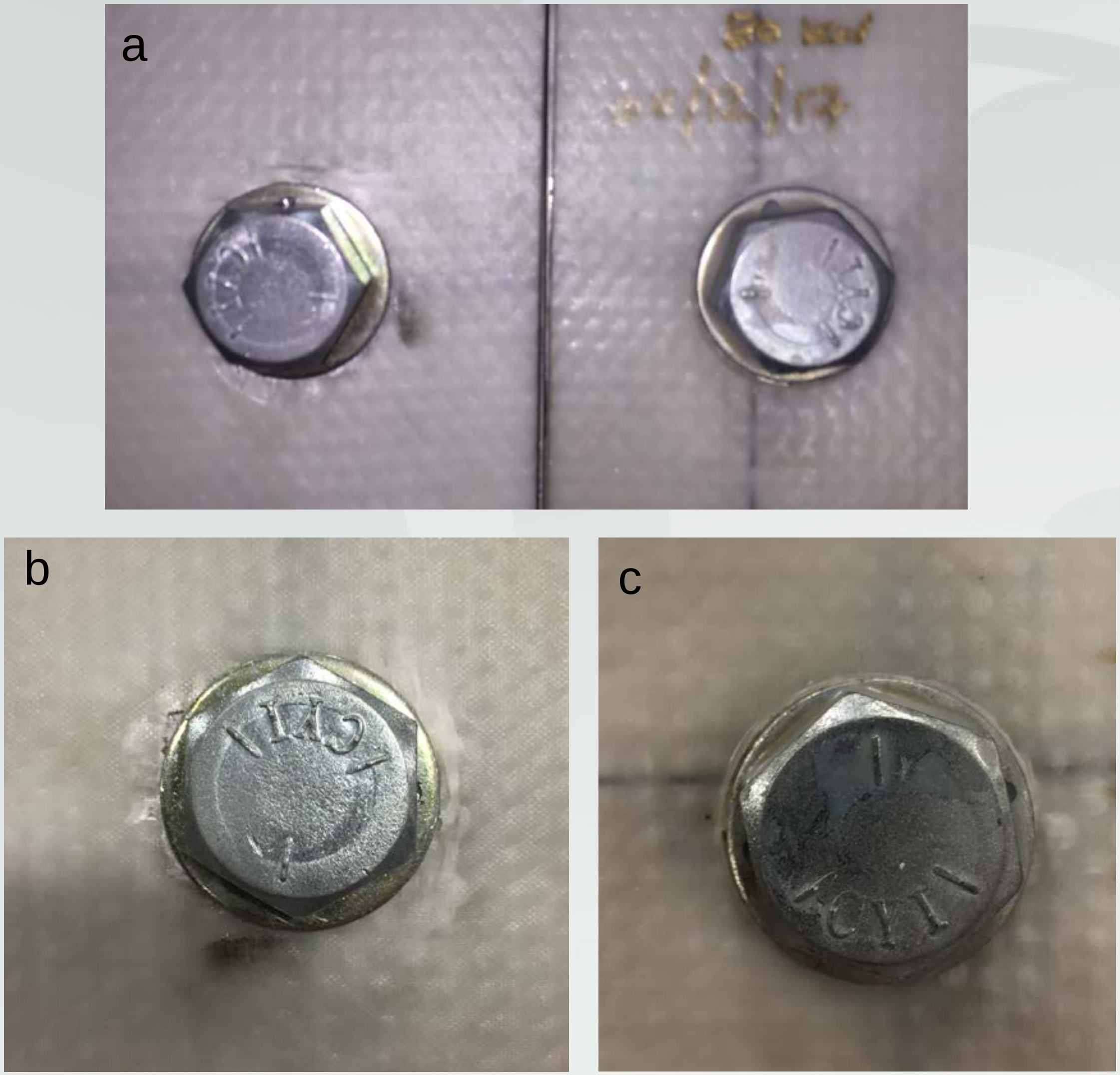
0.75" Diameter bolt – Hybrid vs Control Joints





- Considerable increase of stiffness in hybrid joints
- If slip is critical the hybrid bolt can be considered approximately 5x better than the conventional one
- Hardly any delamination has occurred in specimen F_1 compared (see next slide) to the controlled joints

0.75” Diameter Bolt – Failure Modes



a) After reaching the **80 kN** load max of MTS, damage can be seen in standard joint on left compared to that of hybrid on the right

b) As shown, delamination has been initiated around the hole

c) The hybrid joint shows no signs of visible damage/delamination around the bolt hole

Summary and Interim Conclusions

- A novel hybrid joining technique that incorporates the advantages of both bonded (lightweight, elimination of stress concentrations due to holes) and bolted (easy disassembly) techniques was studied on multi-material joints.
- Novel, hybrid joints did NOT show any SLIP (bolt-substrate movement)
- Considering slip as failure, hybrid joints performed as high as 10x better for smaller diameter (ϕ=0.25”) holes and 5x better for larger joints (ϕ=0.75”)
- Consistently large enhancement in joint stiffness was observed for all hybrid joints relative to conventional joints

Summary and Interim Conclusions

- The 0.75" Diameter hybrid bolt experienced nearly no delamination or damage for peak loads of up to 80kN relative to the control joint that exhibited considerable delamination.
- The waterjet cutting of holes in fiber reinforced substrates creates delamination that upon loading become points of failure initiation. The resin in the adhesive insert fills all voids/cracks/delaminations and heals the material leading to enhanced properties.
- ***Reduction in Weight & Number of holes:*** Increase in load-carrying capacity, increased stiffness, delayed delamination allows possible reduction in bolt numbers, or sizes of the bolts. Lesser holes advantageous in composites!

Future Work: R&D gaps

Short-term:

- Testing on an MTS with more capacity then 80 kN and to look at larger bolt diameters
- Inclusion of FRP sleeves in clearance along with adhesive insert.
- Look at different ways to center the bolt within the cavity

Long-term:

- Fundamental understanding of mechanics of fastener inserts and hybrid joining
- Properly tailor the joint for the application
- Optimum size of insert, insert type and sleeve material(s)
- Optimum adhesive patch for hybrid system
- Correct failure criteria
- Suitable experimentally validated models
- Manufacturing parameters and procedures, including cost.

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Personnel / Team:

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- Mr. Ben Swanson

Thank You

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