Chapter 25
Novel Hybrid Fastening System with Nano-additive Reinforced Adhesive Inserts

Mahmoodul Haq, Anton Khomenko, and Gary L. Cloud

Abstract Structural joining of materials and components involves complex phenomena and interactions between several elements of either similar or dissimilar materials. This complex behavior, coupled with the need for lightweight structures and safety (human occupants in aerospace, automotive and ground vehicles), propels the need for better understanding and efficient design. A novel joining technique that incorporates the advantages of both bonded (lightweight) and bolted (easy disassembly) techniques was invented (Provisional Patent 61/658,163) by Dr. Gary Cloud at Michigan State University. The most basic configuration of this invention consists of a bolt that has a channel machined through the bolt-shaft that allows injection of an insert compound that fills the hole-clearance of the work-pieces and acts a structural component. The hole may contain additional sleeves or inserts. Several combinations of the proposed technique are possible, and in particular, the effect of the adhesive inserts, with and without nano-modification was studied in this work. Glass Fiber Reinforced Plastic (GFRP) composite plates were used as adherends with 12.5 mm holes, grade 8 bolts and preloaded to a torque of 35 N m. Pristine and Cloisite® 30B nanoclay reinforced SC-15 epoxy were used as adhesive inserts in the hybrid bolts. Tension lap-shear tests were performed on conventional (no-inserts) and hybrid bolted joints (inserts: adhesives + nanoclay), and their performance was compared. Results reveal that hybrid bolted joints can eliminate joint slip and considerably delay the onset of delamination. The addition of nanoclay increases the strengths but most importantly can prevent moisture from reaching the bolts shaft due to its excellent barrier properties. The proposed joining technique holds great promise for multi-material joining and a wide range of applications.

Keywords Novel joining technique • Hybrid bolted joint • Nano-modification • Cloisite® 30B nanoclay • SC-15 epoxy resin

25.1 Introduction

Lightweight and reliable dissimilar material joining is of special interest in automotive, aerospace, defense and marine industries. Conventional and well-established methods for dissimilar materials joining include friction stir welding (FSW), ultrasonic welding, arc welding, laser welding, plasma welding, explosive welding/bonding using chemical explosives, conventional brazing or soldering, rivets, bolts, and other conventional mechanical fasteners, and conventional adhesive joining [1]. However, each of those techniques has its own advantages and drawbacks.

FSW is widely used as its solid-state nature leads to number of advantages over fusion welding methods since porosity, solute redistribution, solidification cracking and liquation cracking do not arise during FSW [2]. Ultrasonic welding is well-established technique for joining both hard and soft plastics, such as semi-crystalline plastics, and metals [3]. But, it cannot allow joining for thick materials, making it difficult to join metals. Arc welding technique is not complicated and very well established, therefore it remains an important process for the fabrication of steel structures and vehicles [4, 5]. However, metallic corrosion in the weld area is a big concern. Other types of welding such as laser welding [5], plasma welding [6], explosive welding/bonding using chemical explosives [7], conventional brazing or soldering [8] all share the most common limitations of inability to join metals to FRP composites.

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Mechanical joining is one of the oldest, most important, and most neglected aspects of engineering design of machines and structures of all types and sizes. Such fasteners offer the advantage of being able to be removed without destroying the structure and they are not sensitive to surface preparation, service temperature, or humidity. On the other hand, bolts increase the weight of the resulting joint and create potential sources of stress concentration within the joint [9]. Moreover, the drilling of holes in laminated composites creates the serious problem of delamination in the joint, plus the clearance of the hole and the bolt can lead to bolt-adherend slip which is a serious concern in load re-distribution and stability of resulting components.

Adhesively bonded joints are gaining popularity in place of conventional fasteners as they provide light weight designs, reduce stress concentrations, enable joining of dissimilar materials, and are often cheaper than conventional fasteners. Bonded joints provide larger contact area than bolted joints thereby providing efficient stress distribution enabling higher efficiency and improved fatigue life [10]. Nevertheless, the quality of adhesively bonded joints depends on various factors including manufacturing techniques, manufacturing defects, physical damage and deterioration due to accidental impacts, moisture absorption, improper handling, etc. These factors can significantly affect the strength of resulting bonded joints and a successful monitoring technique that can provide information about the adhesive layer and its resulting joint is essential. Moreover, the resulting joint cannot be disassembled or reassembled anymore.

The joining technique presented in this work aims at overcoming the limitations of conventional joining techniques and incorporates the advantages of both bonded (lightweight) and bolted (easy disassembly) techniques. This novel technique was invented (Provisional Patent 61/658,163) by Dr. Gary Cloud at Michigan State University, and the first concept of the hybrid bolted joining was proposed in [9]. This system is particularly effective for applications in automotive, marine, air, and ground vehicles that are subject to severe service environments. As mentioned earlier, this technique has the advantages of both the adhesive and mechanical joining techniques, such as easy installation, repair and replacement, minimization of stress-concentration around holes, prevention of delamination in composites, and reduction of overall weight. Additionally, the use of structural inserts, specifically bonded inserts, allows filling of any delaminations or defects, reduces stress concentrations, creates compliance between adherends and introduces the advantages of adhesive bonding into the system. Most importantly, this technique can incorporate dissimilar material adherends efficiently. The tailorable nature of this technique allows selection of sleeve/insert that will create maximum compatibility among the dissimilar adherends and eliminate premature failures. Furthermore, the structural insert/sleeve can be tailored to modify the performance of resulting joints. Such joints need not be considered a weakness anymore, but rather a strength to control the overall structural behavior.

In this work, the effect of nano-modification of adhesive insert on the hybrid bolted joint behavior was studied. Tension lap-shear tests were performed on conventional (no-inserts) and hybrid bolted joints (inserts: pristine adhesive, and nanoclay reinforced adhesive), and their performance was compared. Results reveal that hybrid bolted joints eliminate joint slip and considerably delay the onset of delamination. The addition of nanoclay increases the strengths, but most importantly can prevent moisture from reaching the bolt shaft due to its excellent barrier properties. The proposed joining technique holds great promise for multi-material joining and a wide range of applications.

25.2 Hybrid Bolted Joining Technique and Sample Preparation

The most basic configuration of this invention (see Fig. 25.1) consists of a bolt that has a channel machined through the bolt-shaft that allows injection of an insert compound that fills the hole-clearance of the work-pieces and acts a structural component. The hole may contain additional sleeves or inserts.

In this work, the vacuum assisted resin transfer molding (VARTM) technique was used to manufacture the composite adherends for the lap joints. The reinforcement used for the adherend was S2-glass plain weave fabric (Owens Corning ShieldStrand S) with areal weight of 818 g/m^2. The resin used was a two part toughened epoxy, namely SC-15 (Applied Poleramics Inc., CA). Cloisite® 30B (Southern Clay Products, Inc., TX) with 2.5 wt% concentration was used as nano-reinforcement of the resin. The adherend had 16-layers of plain weave fabric with a resulting thickness of ~10 mm.

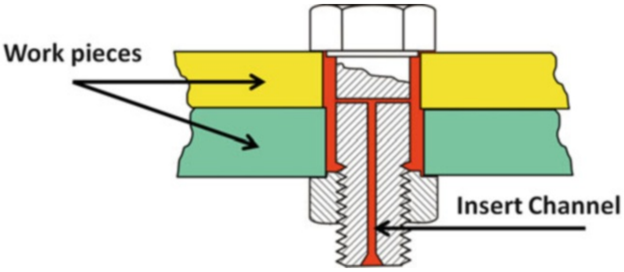


Fig. 25.1 Basic configuration of proposed hybrid bolted joining system

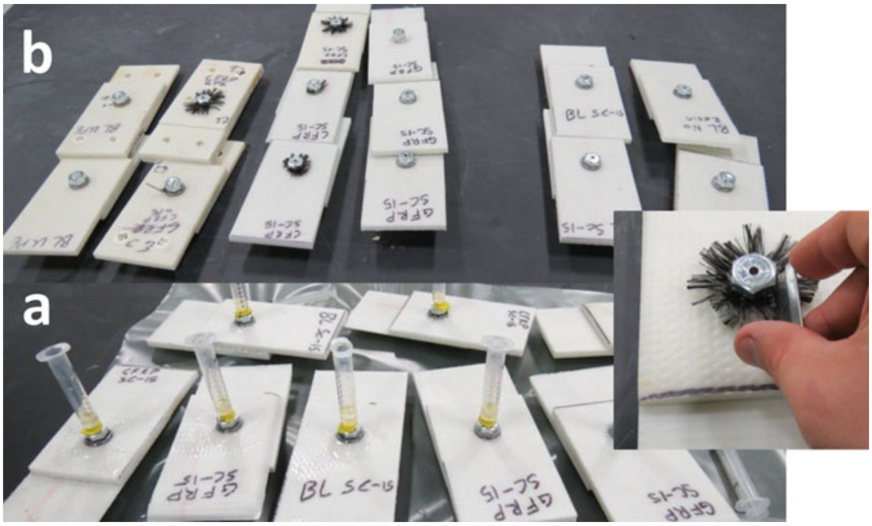


Fig. 25.2 (**a**) Manufacturing of hybrid bolted joints, (**b**) manufactured hybrid bolted joints

The adherend/plates were joined using ordinary grade 8 nominal 1/2 in. bolts and matching flat washers. Conventional bolted joints had no insert, and the bolts were not drilled. Bolts with drilled 2 mm diameter passageways for resin injection were used for the remaining specimens. All the bolts were torqued to 35 N m.

The nano-modification of SC-15 epoxy involved homogeneous mixing, and exfoliation of nanoclay in the resin. Initially, part A of SC-15 epoxy was mixed with the desired nanoclay content (2.5 wt%) and the resulting compound was sonicated using Vibra-Cell™ sonicator for around 30 min until the total applied energy was 30 kJ. Intermittent sonication energy (10 s energy: 5 s pause) was applied to control the rise in temperature of compound. Once 30 kJ was applied, the resulting mixture was cooled at room temperature for 10 min, followed by mixing of part B of SC-15 epoxy. The solution was mixed thoroughly, degassed and was made available for injection in the hybrid joining system. Once the adherends were joined with the applied torque level (35 N m), the pristine/n-modified resin was injected through the bolt, and the joint was cured in a convection oven at 60 °C for 2 h followed by post curing at 94 °C for 4 h.

Figure 25.2a, b illustrate the manufacturing process and resulting hybrid bolted joints respectively.

25.3 Experimental Results and Discussion

Three case studies were performed in this work, namely: (a) the conventional joint (control specimen), (b) the hybrid joint-pristine adhesive, and (c) the hybrid joint-nanoclay reinforced adhesive. The resulting lap-joints were tested in tensile-shear configuration until failure in displacement control at a rate of 1 mm/min. The displacement and applied load from MTS were recorded. Additionally, an external laser extensometer (LE-05 Epsilontech Laser Extensometer) was used to obtain precise relative displacements between the adherends.

25.3.1 Hybrid Bolted Joint with SC-15 Insert

In the first set of experiments, the performance of hybrid bolted joints with just SC-15 adhesive insert (no nano-modification) was compared to conventional bolted joints with no insert (see Fig. 25.3).

A few critical observations are highlighted in the plot in Fig. 25.3 to efficiently compare their performance. First, the graph for the conventional bolted joint shows a significant slip around 7 kN, where the applied tensile-shear load is sufficient to overcome the clamping forces (see Fig. 25.3, feature 1). At ~20 kN load, onset of delamination occurs in the vicinity of the point of contacts of the bolts with the adherend (see Fig. 25.3, feature 2). As the applied load increases, the delamination continues (see Fig. 25.3, feature 3), the washer deforms, and the bolt bends up to a maximum load of about 46 kN (see Fig. 25.3, feature 4). The delamination continues but the load carrying capacity considerably reduces after the peak load. Depending upon the desired application, the initial slip or reduction in load carrying capacity after peak load can be

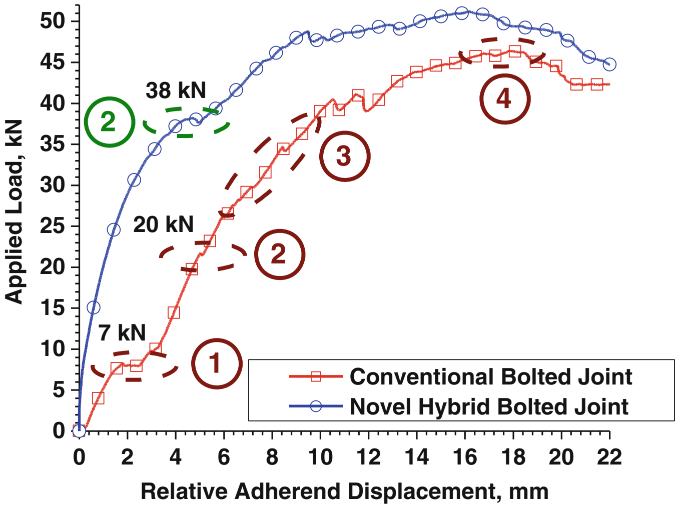


Fig. 25.3 Comparison of conventional bolted joint with novel hybrid bolted joint and some salient features: 1—joint slip, 2—onset of delamination, 3—growth of delamination, 4—maximum load capacity

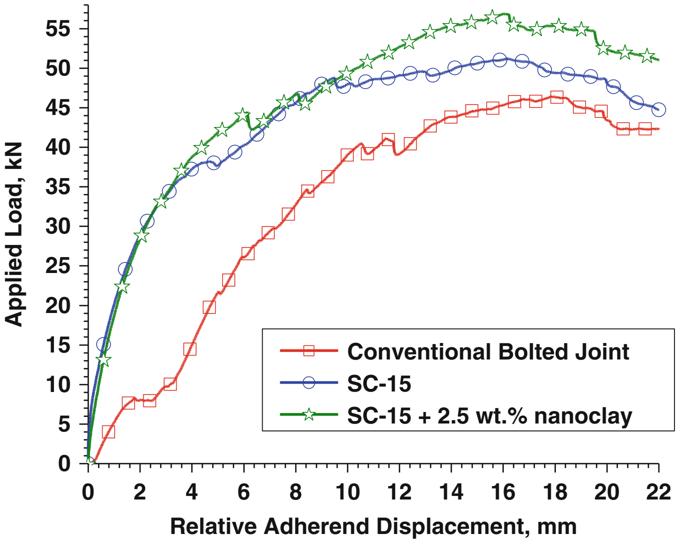


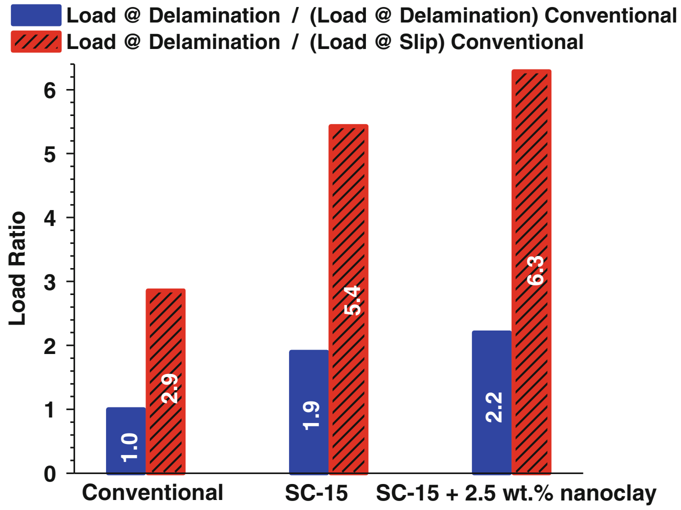
Fig. 25.4 Comparison of hybrid bolted joints containing nano-clay reinforced adhesive insert with hybrid bolted joint containing pristine adhesive and conventional bolted joint

considered as ultimate/failure loads for design purposes. Now, let's examine the response for the joint having pristine adhesive insert. Firstly, this joint does not exhibit any slip, and shows an increased stiffness up to 38 kN where the onset of delamination occurs. After the onset of delamination, the stiffness reduces, but the load-carrying capacity continues to increase up to 49 kN. Beyond this, similar to conventional joints, the delamination continues without any resistance to applied load until total joint destruction. Comparison of these data suggests that joint performance is enhanced although a simple, relatively "soft" adhesive insert is used. The degree of improvement can be further increased/tailored by using the appropriate structural adhesives. Furthermore, if slip is critical, then the joint with the adhesive can be considered infinitely better than the conventional one. If failure is defined as the onset of delamination, then the joint with the adhesive insert is ~90 % better. Similarly, if joint stiffness is the criterion, then the joints with adhesive insert perform better. Most importantly, the adhesive can be selected to tailor the performance of the joint and the resulting structures.

25.3.2 Hybrid Bolted Joint with Cloisite® 30B Modified SC-15 Insert

In the second set of experiments, the performance of hybrid bolted joints containing nanoclay reinforced adhesive insert was compared with both conventional and hybrid bolted joints containing pristine adhesive (see Fig. 25.4). The comparison of nanoclay reinforced adhesive insert and conventional bolted joint is analogous to that described for pristine adhesive insert

Fig. 25.5 Comparison of delamination and slip loads for novel hybrid joints relative to conventional bolted joint



joint (see previous section, Fig. 25.3). Nevertheless, the comparison of hybrid joints with pristine and nanoclay reinforced adhesive inserts reveals delay in onset of delamination. This can be attributed to the increase in toughness of the adhesive due to nanoclay reinforcement. Additionally, nanoclay reinforcements introduce tortuosity and crack-bridging properties that can further reduce brittleness and increase toughness.

As mentioned earlier, depending on applications, either the onset of slip or the onset of delamination can be considered as the failure load for design purposes. Hence comparisons of the hybrid joints in this study with the onset of slip and onset of delamination in conventional joint are shown in Fig. 25.5. If the onset of slip is considered, the hybrid bolted joints perform ~5 to 6 times better than conventional joint. If the onset of delamination is considered, the hybrid bolted joints with adhesive inserts perform ~2 times better. The effects of nanoclay are quite prominent considering the small addition of nanoclay (in this case 2.5 wt%) with increase in both the ultimate load carrying capacity and the load at onset of delamination in bolted joints relative to their counterpart with just pristine adhesive. Furthermore, nanoclay has excellent barrier properties and can considerably reduce moisture diffusion into the joint/bolt-shaft.

Overall, hybrid bolted joints can eliminate joint slip and considerably delay the onset of delamination. In this work, the effect of just adhesive inserts and nanoclay incorporation was explored. Considerable work that includes varying concentrations, different nano-reinforcements, structural adhesives and fiber-reinforced sleeves needs to be performed to fully exploit the benefit offered by this robust joint. Nevertheless, the results shown in this work show great promise for use of these novel hybrid joints for a wide range of multi-material joining applications.

25.4 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. The most basic configuration of this invention consists of a bolt that has a channel machined through the bolt-shaft that allows injection of an insert compound that fills the hole-clearance of the work-pieces and acts a structural component. The effect of an adhesive structural insert was experimentally studied and compared to a conventional bolted joint. Furthermore, both pristine and nanoclay reinforced (2.5 wt%) adhesives were studied. Single lap-joints consisting of S-glass/SC-15 epoxy adherends and joined using ordinary grade 8 nominal 1/2 in. bolts and matching flat washers were manufactured and tested under tensile-shear configuration. Results revealed that the novel hybrid joints did not exhibit any joint-slip and had considerably higher load carrying capacities prior to onset of delamination, relative to conventional joints. If the onset of slip is considered, the hybrid bolted joints perform ~5 to 6 times better than conventional joint. If the onset of delamination is considered, the hybrid bolted joints with adhesive inserts perform ~2 times better. The effects of nanoclay are quite prominent considering the small addition of nanoclay (in this case 2.5 wt%) with increase in both the ultimate load carrying capacity and the load at onset of delamination relative to joints with just pristine adhesive. Furthermore, nanoclay has excellent barrier properties and can considerably reduce moisture diffusion into the joint/bolt-shaft. Considerable work that includes varying concentrations, different nano-reinforcements, structural adhesives and fiber-reinforced sleeves needs to be performed to fully exploit the benefit offered by this robust joint. Nevertheless, the results shown in this work show great promise for use of these novel hybrid joints for a wide range of multi-material joining applications.

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