AN EXPERIMENTAL PARAMETRIC STUDY ON THE EFFICIENCY OF HYBRID FASTENING SYSTEM

By

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ABSTRACT

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As the use of fiber-reinforced polymer composites in mass-produced structural components in all domains of industry has grown, appropriate advancements in joining systems are necessary. Bolted joints are a common method used due to the simplicity of the process. Drilling holes in composites for fastening results in delamination, creation of locations for the onset of failure, and can reduce load-carrying capacities. Hybrid fastening techniques and other approaches for joining composite materials have been developed as a way to address problems related to conventional bolted joints. One such technique is the hybrid fastening system in which a structural adhesive insert is placed in the bolt-hole clearance. This approach has been shown to eliminate bolt-adherend slip, reduce delamination, and increase load-bearing capacities. Nevertheless, the extant work on such a hybrid fastening system is limited.

In this work, experimental characterizations of hybrid fastening systems comprised of glass fiber reinforced polymer (GFRP) composite substrates fastened using a fully threaded grade 5 steel bolts in ½” (12.5 mm.) diameter with varying bolt hole clearance and three structural insert materials were performed. The GFRP substrates were manufactured using the vacuum-assisted resin transfer molding (VARTM) process. The preload was maintained at 75% of the bolt yield strength for all joints. The objective of this work was to characterize/quantify the effect of: a) the adhesive insert and b) the bolt-hole clearances on the efficiency of the hybrid fastening system. For the first parameter, namely the effect of the adhesive insert, four configurations, namely the hybrid fastening system with three different structural insert materials and one

control/conventional joint without any structural insert were studied. Adhesive insert materials used were PRO-SET epoxy resin, DEVCON epoxy carrying aluminum particles, and polyurethane. All resulting joints were cured at room temperature for 48h prior to testing. For the second parameter, namely the effect of bolt clearance, four different bolt-hole clearances: close fit (0.5mm), normal fit (1.0 mm.), loose fit (1.5 mm.), and extra loose fit (2.0 mm.) were studied for each of the insert materials along with the control/conventional joint without any structural insert. The resulting joints were tested in a tensile-shear configuration at a rate of 5 mm./min.

Hybrid joints were found to have 7 to 9 times higher load carrying capacities relative to slip-loads for conventional joints. All hybrid fastening systems showed no bolt-adherend slip along with delayed onset of delamination relative to conventional joints. Most of the joints with close fit (0.5mm) clearance were found to experience a catastrophic failure which resulted in bolt shearing failure. All other joints experienced progressive delamination failure without any bolt-shear failures. Further, the results indicate that the failure mechanism changed with the changes of bolt-hole clearances. The larger the clearances, the more the bolt tilts/rotates and experiences a combination of bending and shear. For small clearances, such as close-fit, shear dominates and bolt-shear occurs leading to bolt fracture. The combination of slightly larger clearance along with a structural adhesive insert allows tailoring the bolt- joint performance, leading to 7-9 times better performance than conventional joints with similar clearances. Future work should focus on quantifying the stress-concentrations and its reductions due to the addition of structural inserts. Overall, this work is novel and the first to report on the effect on clearance and varying adhesive insert materials for hybrid mechanical joints.

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To beloved peoples who have meant and continue to mean so much to me.
Nazrul Aizad, Naufal Syafi, Nia Syifa, Abah & Mak
Thank you for the prayers, sacrifices and supports

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Chapter 1: Introduction

1.1. Motivation

Joining has been identified as one of the driving technologies for innovation and sustainable manufacturing [1],[2]. Messler [3] defines joining to be: ‘‘The process used to bring separate parts of components together to produce a unified whole assembly or structural entity’’. Poor design of structural joints can lead to noise, vibration, problems with load transfer, localized stress concentrations, fatigue, and catastrophic failure. Thus, the choice and design of fastening systems is important in order to increase manufacturing efficiency [1, 3] and to maintain structural integrity.

There are a great many joining techniques, and these may be divided into 3 broad classes, namely: mechanical fastening, adhesive bonding, and welding. Some joints are permanent and cannot be dis-assembled for maintenance or repair. Examples of such permanent joining include adhesive bonding and welding. Other fastening devices, including bolts and cap screws, facilitate disassembly for inspection, structural repair, or component replacement. Enhancing the performance of these mechanical fastening systems is the subject of this dissertation.

Bolts and cap screws are the most commonly used mechanical techniques to join or secure components due to the simplicity of the processes involved, their established dependability, and their long history of evolution and refinement [4]. One of the biggest advantages of bolted joints is their ease of assembly and disassembly in factory and field using simple tools. Furthermore, extensive surface preparation is not required.

However, mechanical fastening has some limitations. The use of fasteners in joining the parts can limit weight savings. One example from the past is instructive: 18,000 mechanical fasteners are used in the F-18 fighter jet airplane, and the weight of the fasteners alone is approximately 500 lbs [6]. The fasteners account for 1/3 of the total cost of a typical commercial airplane, the same as the engines [6]. Drilling holes for bolts will introduce stress concentrations, which can lead to strength degradation and introduce corrosion related problems[6].

There is a continuous demand in the automotive, aerospace and marine industries for joining parts made of similar and dissimilar materials [5,7]. Some of the objectives involved in dissimilar material joints are to enhance product design flexibility and to enhance the structural and functional efficiencies. For efficient manufacturing of lightweight structures, it is essential to understand the potential of different joining techniques [5]. There are several joining techniques that are used to join metal and polymer-based materials. These techniques can be used individually or combined to address the flaws or challenges involved in conventional joints. However, it should be noted that these emerging techniques have their advantages and disadvantages, and the most appropriate method depends on the application and service requirements.

Several parameters need to be considered in mechanical fastening to ensure efficient performance of the joints. This include material thickness, fastener types (bolt, cap screw, rivet), material properties (e.g. composite to composite / composite to metal), hybrid joining (mechanical plus adhesives), preload clamping, loss of preload due to creep and relaxation, fastener size and scaling effects, bolt-hole clearance, interference fits, tapered threads, washers (flat, spring, conical), hole shape (non-round holes, tapered holes, etc.), fastener shape (non-cylindrical, tapered, etc.), hole treatment (coldworked, peened), insert and bushings, fastener arrays (shape and spacing), edge distance, torque (shear) effect upon tightening (especially for laminates), blind fasteners (one-side access) and manufacturing methods [6].

Hybrid fastening techniques and approaches for joining dissimilar materials have been developed to address problems arising in more traditional fastening techniques. Earlier work on a novel hybrid fastening system, which introduces a structural resin insert injected through a channel in the bolt shaft as a structural element, overcomes the effects of drilling, eliminates slip, reduces delamination and increases the load-carrying capacities [6]. To name but four examples, Herrera and Cloud[19], Camanho, et al. [8], Koricho et al. [9] , and Kelly [10] in their studies showed that an insert used in a composite joint was able to reduce the stress concentration surrounding the bolt holes and improve fatigue behavior. The basic concept of a structural insert filling the bolt clearance is examined in these studies. This structural insert fills the delaminations introduced during the drilling process and acts as a protective layer to arrest premature failure or disaster [6,9]. Figures 1-1 and Figure 1-2 from the work of Herrara and Cloud [19] and Cloud [6] show the stress concentrations around the bolt hole and the role of inserts in reducing them. Nevertheless, the efficiency of hybrid fastening systems on the effect of bolt-hole clearance and varying adhesive insert material have not been studied or fully characterized.

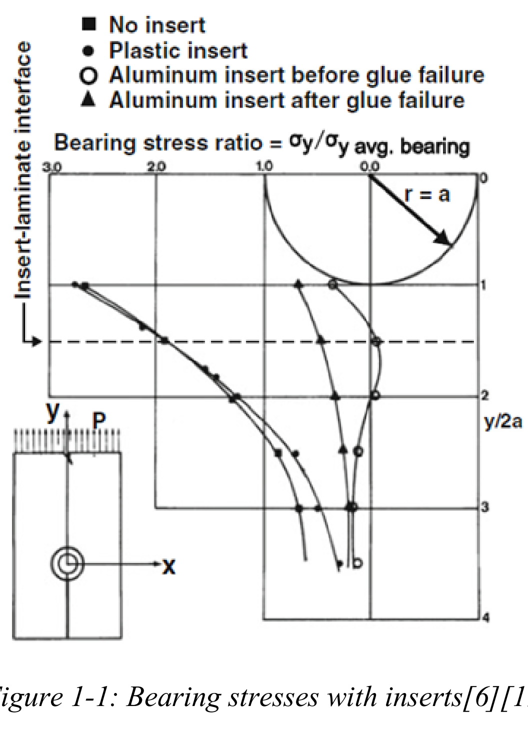


Figure 1-1: Bearing stresses with inserts[6][19].

Therefore, the efficiency of a hybrid fastening system with varying structural insert materials and varying bolt-hole clearance with similar substrates was investigated in this study. Structural inserts will be introduced to create a hybrid fastening system. The insert materials that have been proposed are two-part epoxy (same as the resin used to manufacture the substrates), poly-urethane and epoxy with aluminum reinforcement.

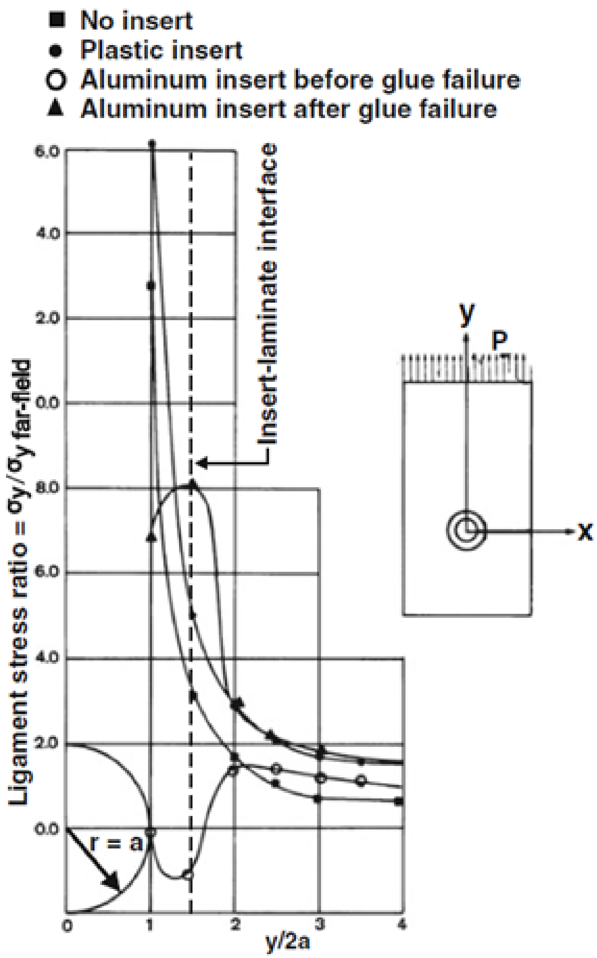


Figure 1-2: Ligament stresses with inserts[6][19].

1.2. Objectives

The goal of this work is to investigate the improvements in performance, if any, gained by a mechanical hybrid fastening system that incorporates an injected resin insert. The effects of varying insert material and bolt hole clearances on joint static strength are investigated. Uniform substrate material (a glass fiber reinforced plastic (GFRP)) was used to reduce the complexity of the study.

The basic concept of the injected hybrid fastener system using resins or resins containing adjuncts as structural inserts has been described in papers and patents by Cloud [[6], [11],[12]]. The tasks to be executed towards the accomplishment of this work are listed below and are also shown schematically in Figure 1-3.

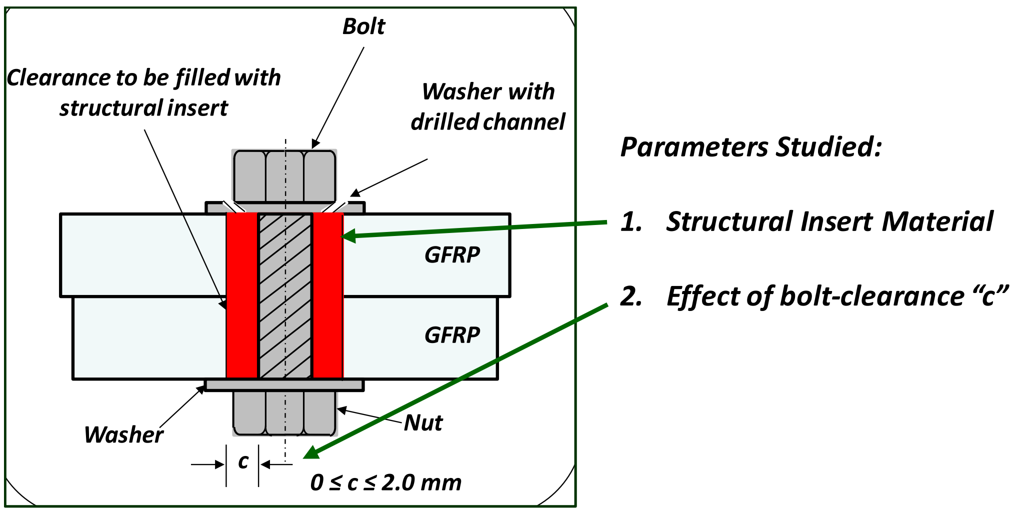


Figure 1-3:. Schematic of parameters studied in this work.

The overall objectives of the work can be summarized as follows.

- To study the effect on the strength of a composite hybrid fastening system of varying insert material with constant bolt diameter and various insert material thicknesses,
- To study the effect on the strength of a composite hybrid fastening system of varying bolt hole clearance / insert material thickness with constant bolt diameter and with respect to different insert materials,

1.3. Brief Literature Review

Composite materials are being used increasingly in several applications in aerospace, ship building, automotive, bridge construction and other engineering domains where light weight, stiffness and strength properties are of primary concern[14][15][16]. Mechanical fastening is one of the commonly used joining techniques because of its manufacturing ease and the confidence in its performance acquired through decades of experience. Joints are a critical part of a structure and it is important to consider all the design parameters to ensure safety [14]. As mentioned, one of the main advantages of mechanical fastening is the ease of assembly and disassembly. However, drilling holes in composite laminates may result in larger stress concentrations around the holes by virtue of the material's high degree of anisotropy and drilling induced defects. Furthermore, the strength of composite laminates will be diminished due to the presence of a fastener hole [17][18].

It is known that mechanical fastenings are more efficient in metallic structures than in composites. This can be attributed to the ductility of metallic materials. The expected stress concentrations that occur at bolt holes can be substantially relieved through localized plastic yielding of the metal in the vicinity of the holes. By contrast, in composite structures, there is only limited stress relief through plastic yielding. Fracture therefore typically occurs at a lower load and at a lower ratio of joint-strength-to-adherend-strength.

The design of a mechanical fastening for a composite is more complex than is the case for metallic materials. The effects on performance of several parameters related to the composite material need to be considered. These include, among others, fiber and matrix type, lay-up, bolt-hole clearance, stacking sequence, bolt type, joint geometry and torque applied [7]. In a typical joint manufactured using composite materials, the strength efficiency is 25 % lesser than that of its metallic counterparts[17][19]. This can be attributed to the high stress concentrations around the hole and the damage induced in composite materials during the drilling process. As mentioned above, in contrast to composite materials, yielding in metallic materials reduces localized high stresses and redistributes the stresses[17].

One of the several challenges involved in composite joint manufacturing is the drilling process. It introduces stress concentrations and delamination that reduce the overall load carrying capability. Furthermore, these defects will become the points of failure during the loading process. Hence, it is important to devise novel techniques to relieve the stress concentrations and to heal or limit the defects.

One solution is to incorporate bonded or unbonded inserts into the hole, these inserts filling the gap between the bolt shank and the inner surface of the hole. Such inserts act as a protective layer which favorably modifies the local stress distribution and increases the strength of the joint [17]. Herrera et al. [19] measured strains and stress concentration in the vicinity of fastener holes in FGRP that carried bonded and unbonded inserts in the form of thin bushings of aluminum and resins. They found that stresses were reduced to varying degrees, depending on the insert material and the bonding. In one case, the stress concentration attained a negative value near the hole, a startling result.

In order to increase bolted joint efficiency, several researchers have proposed the use of metallic inserts, either interference fit or bonded in between the bolt and the composite laminate. Metallic inserts have shown by many investigators to yield remarkable benefits in reducing stress concentrations around laminate holes [6][8][9][10][17][19][20][21][22][23][24]. The insert helps to redistribute the stresses and strains around the hole, particularly if the adhesive bond does not fail. In all cases, the efficiency of bolted joints with inserts showed better performance when compared with conventional bolted joints, and the increase in strength is reported to vary from 10% to 100% [20][22].

1.3.1. Mechanisms in Mechanical Fastening

Drilling holes in a composite laminate creates stress concentrations, thus the overall load bearing capability of the laminate is severely reduced. The five common failure modes in a mechanical fastening system, illustrated in Figure 1-4, are tension, shear, cleavage, bearing and pull-through. Net tension failures occur when the bolt diameter is an overly large fraction of the strip width. Acceptable fractions are dependent on the type of material and the lay-up used. Bearing failures govern when the bolt diameter is a small fraction of plate width. This type of failure lead to elongation of the bolt hole. Shear failure can be classified as special kind of bearing failure. This failure can occur even with a very large end distance for highly orthotropic laminates. Cleavage failures are associated with both inadequate end distance and too few transverse plies. Pull-through failures can occur when countersunk fasteners are used and when significant bending loads are imposed.

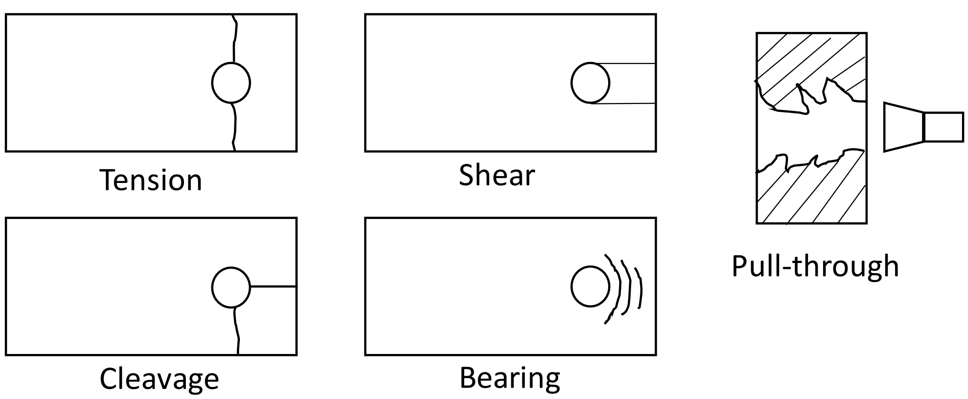


Figure 1-4: Failure modes in composite bolted joints.

Figure 1-5 shows the schematic of a single shear lap joint. The key dimensions are;

d; fastener diameter

t; thickness of the joint elements

w; width of the plate

e; edge distance

P; load

Dt; bearing area loaded in compression

2et; total shear-out area loaded in shear

($w - d$)t; net section area loaded in tension

wt; gross section area loaded in tension

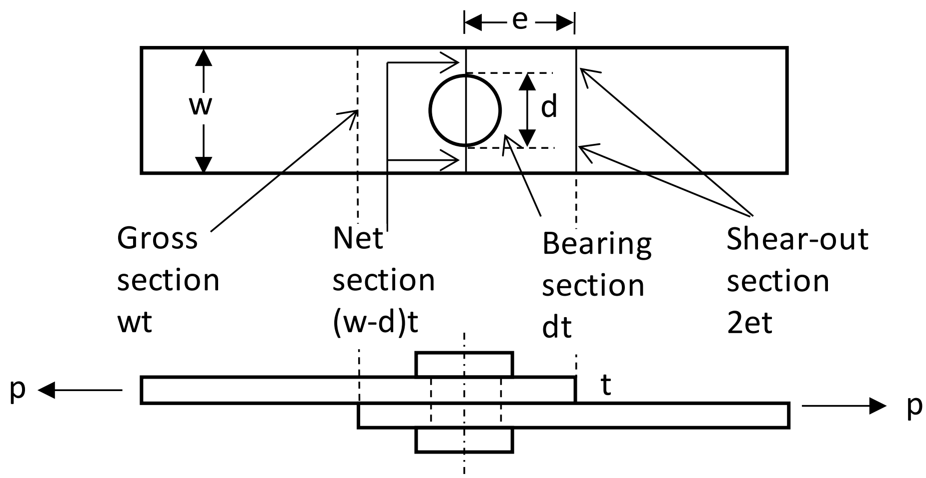


Figure 1-5: Single shear joint.

The important stresses in bolted joints are categorized into bearing, shear-out, net and gross stress. These stresses are calculated using the equations below;

Shear-out stress, $\sigma_s = \frac{P}{2et}$

Net normal stress, $\sigma_n = \frac{P}{(w-d)t}$

Gross normal stress, $\sigma_g = \frac{P}{wt}$

Bearing stress, $\sigma_b = \frac{P}{dt}$

Bearing stress is the average compressive stress that is produced at the surface of contact between the bolt and the substrate when they are fastened together. It is developed due to the load, P which ultimately affects the hole in the plate as shown in Figure 1-6. Bearing stress is also known as crushing stress. Bearing failures are characterized by localized damage, such as delamination and matrix crazing around the hole. These failures occur by the fastener causing localized compression loading leading to buckling and kinking of the fibers followed by crushing of the matrix.

The equation for bearing stress considers the stress not evenly distributed into the hole diameter. The stress distribution is more like an elliptical shape, and varies drastically with hole clearance

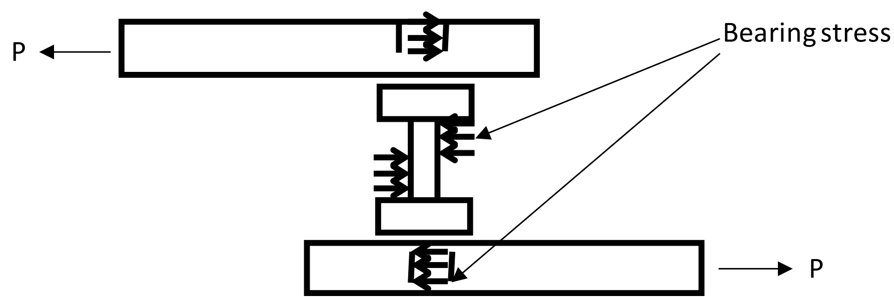


Figure 1-6: Bearing stress in bolted joint.

For most applications, bolts are commonly manufactured of metal, typically steel. When the bolt is tightened, it will stretch and behave like a tension spring, causing a tensile stress in the bolt and a corresponding compressive clamping force in the structure. The behavior of the joint depends on how tightly the bolts clamp and how long they can maintain their preload. If this stretch exceeds the elastic limit or if the joint is overloaded, the bolt yields plastically, acquiring a permanent set. The result can be a loss in preload or clamping force.

The bolt itself can fail in one, two, or a combination of modes. If the loading is in pure shear fit is tight, then the bolt will exhibit shear failure. If bending loads are present or if the fit is loose so as to allow tilting of the bolt, then the failure might be in bending even in tension if the deformations are extreme.

1.3.2. Effect of Insert Material in Bolted Joint

Filling of the clearance between bolt and hole is carried out through a small hole in the head or shank of a bolt or of a washer. After injection of the insert material, it is allowed to cure at room temperature or respective curing conditions. Koricho et al. [9][35] and Haq et al.[36] studied joints of GFRG to GFRP with constant bolt diameter of 0.5”. They used SC15 epoxy as the adhesive insert to fill the bolt-hole clearance. Their study showed that the joints with resin structural inserts eliminate slippage of the joints, and they were found to perform 2-6 times better than conventional joints.

Camanho et al. [24] in their study used adhesively bonded metallic inserts to increase the efficiency of composite bolted joints. The effect on joint strength of two different insert materials, Aluminum 2000 series and mild steel, were determined. The results from their study, reproduced in Figures 1-7, through Figure 1-9, showed that the insert decreased the maximum stresses in the tension and bearing planes. The stresses acting on the laminate surrounding the holes were redistributed. However, for the different configurations investigated, the adhesive failed before the full strength of the laminate was reached. They recommended the use of thinner and more compliant inserts of aluminum rather than steel.

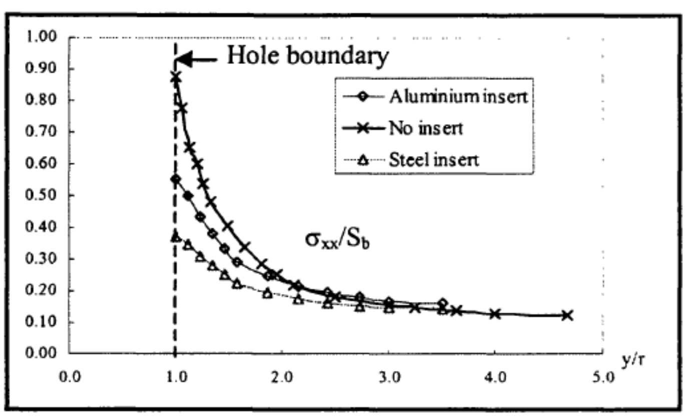


Figure 1-7: Distribution of σ_{xx}/S_b for different insert material along the tension plane for CFRP laminates bolted joint [24].

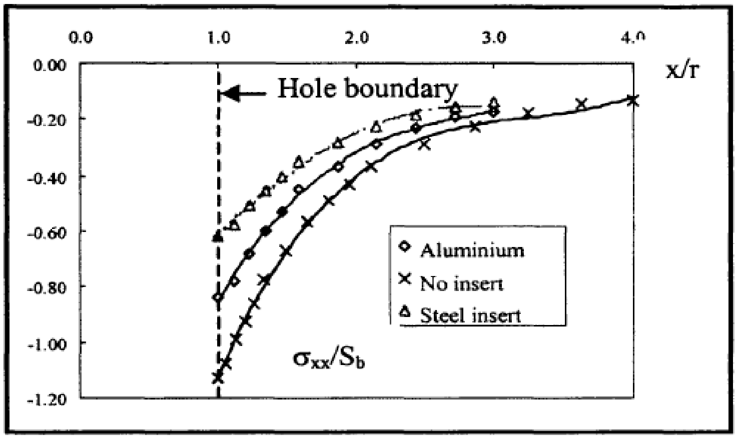


Figure 1-8: Distribution of σxx/Sb for different insert material along the bearing plane for CFRP laminates bolted joint [24].

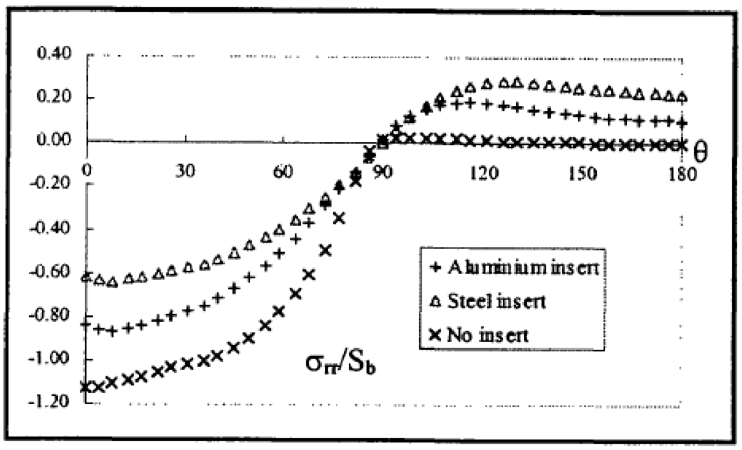
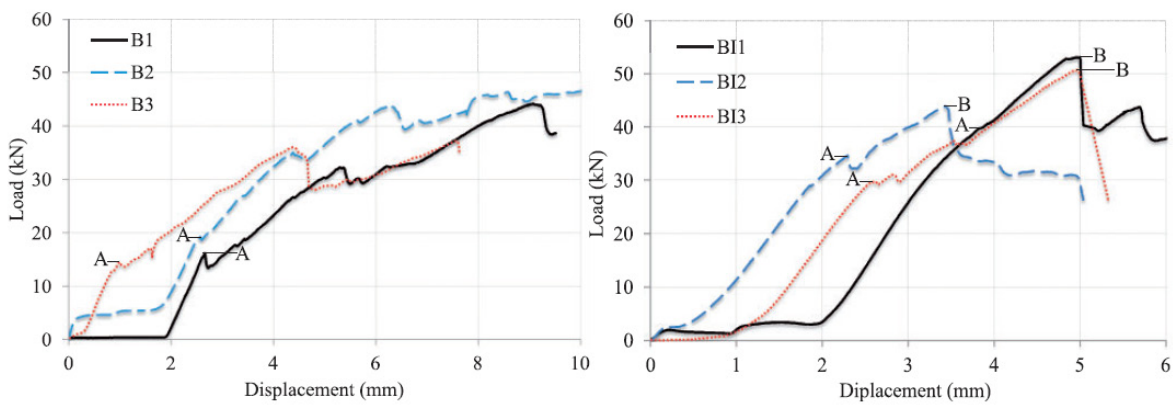


Figure 1-9: Normalized radial stress distribution for CFRP laminates bolted joint [24].

Mara et al. [17] studied the effect of inserts on bolt-tension relaxation, the stiffness, and the load bearing behavior of composite bolted joints. In their study, they used metal inserts and compared the results to conventional bolted joints. The standard steel bolts used in their study were M10, class 8.8 (i.e. yield strength of 640 MPa and ultimate strength of 800 MPa). A clearance of 1mm was chosen for the joint tests based on the common range of clearances used in steel bridges for bolt diameters lower than 14 mm. As a result, a hole of 11mm was drilled in the joints having no inserts, whereas, in the joints with inserts, the hole was 16mm in diameter in order to fit the insert.

The results of their study are shown in Figure 1-10. Three (3) specimen were tested for each case and the joints were only finger-tightened. Slip due to the clearances was observed. The difference in the amount of slip between the tests is due to the position of the bolt in relation to the hole, which was not controlled during the assembly of the joints. As can be seen, for a conventional bolted joint on the B1 specimen shown in Figure 1-10 (a), slip occurred immediately after test initiation, whereas for specimen B2, the slip happened after some load was applied to the joint. After slip, the load-deflection curve increased linearly up until point A was reached. The small drop of load at point A indicated damage initiation of the FRP laminate. Further loading reduced the slope of the curve owing to the progressive damage within the composite substrate.



(a) (b)

Figure 1-10: Load–displacement curves for; (a) conventional bolted joints (B1-B3), (b) bolted joints with inserts (BI1-BI3) [17].

The load–displacement behavior of bolted joints with inserts (BI) can be seen as almost linear up to point A in Figure 1-10 (b). The load at point A indicates the initiation of bearing damage in the laminate. Again, slip occurred because of the clearances. The joints with inserts managed to maintain joint stiffness until bearing damage was initiated, and this occurred in all cases at a load higher than that corresponding to damage initiation in the joints having no inserts. The insert evidently provides lateral constraints, preventing the delamination of the FRP laminates and through-thickness expansion around the hole in the insert area. The damage in the laminate is therefore delayed until it splays outside the diameter of the insert lap, where an expansion of the -thickness of the laminate occurs.

Figure 1-11 shows the comparison of the load–displacement curves between a conventional bolted joint and a bolted joint with a metal insert. The initial slip in the tests was ignored for the sake of comparison. This study showed that the load at initiation of damage for a bolted joint with an insert is more than twice that of conventional bolted joints. The initial stiffness is similar for both the joints. However, the stiffness was significantly reduced in the conventional bolted joints after the initial bearing damage. It should be noted that the bearing area of the joints with inserts are higher due to a larger hole diameter of 16 mm, compared with the conventional bolted joints which had a hole diameter of 11 mm. The maximum load that can be supported by the bolted joints with inserts is therefore expected to be higher.

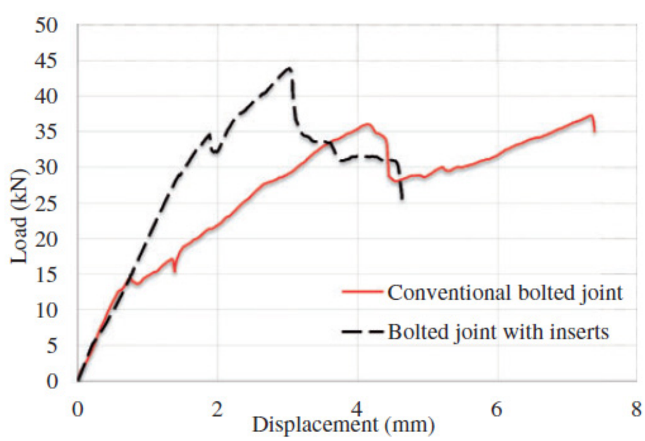


Figure 1-11: Load–displacement curves for a conventional bolted joint and a joint with inserts [17].

Figure 1-12 shows microphotographs of specimens with and without inserts[21]. In this study, bonded metal was used as structural insert for the bolted joint system. Damage can be seen in the laminate of the joint which was manufactured without an insert, whereas no visible damage was evident on the laminate when inserts were used.

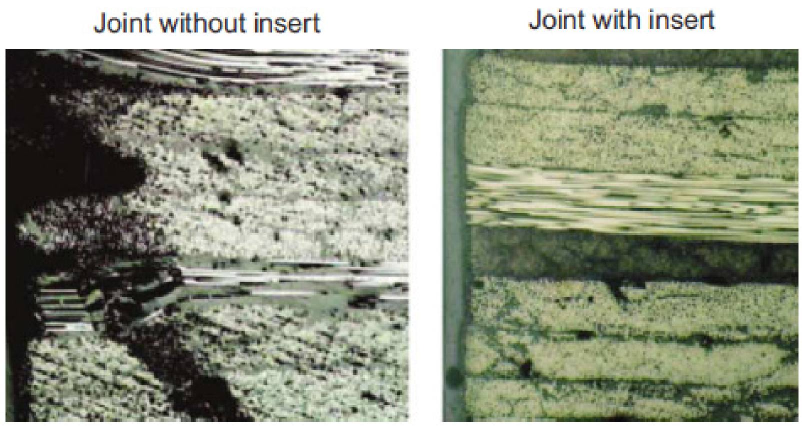


Figure 1-12: Details of micrographs of specimens with and without inserts loaded to 7.5 kN [17].

1.3.3. Effect of Tightening Torque Level in Mechanical Fastening System

The magnitude of the torque applied to the bolt when tightening the joint directly influences the stress fields in both the bolt and the plates. An increment in the increase of torque has major effects on the joint performance. The positive effect is the increase of frictional forces between the substrates that lead to an increase in bearing strength and slip load as proved in [17][24]. The negative effect is due to the out-of-plane crushing stresses that are developed when the torque is applied. This can lead to the premature failure of the joint. However, when joining laminates, some increase of this clamping load can prevent delamination. For conventional joining the maximum value of torque is limited by standards.

Olmedo et al.[27] studied the influence of friction coefficient and tightening torque for single-lap bolted joints using computational models. The model was initially validated through comparison with experimental results from literature. The results showed that the joint strength increased with increase in friction coefficient. For low friction coefficients, the load to produce joint displacement is very low. In this case, joint strength cannot be improved with torque preload. Figures 1-13 and Figure 1-14 show the effect of friction coefficient on joint strength. The effect of torque level is dependent on friction coefficient. It can be clearly seen that for 0.5 friction coefficient, increments of tightening torque increased the joint stiffness.

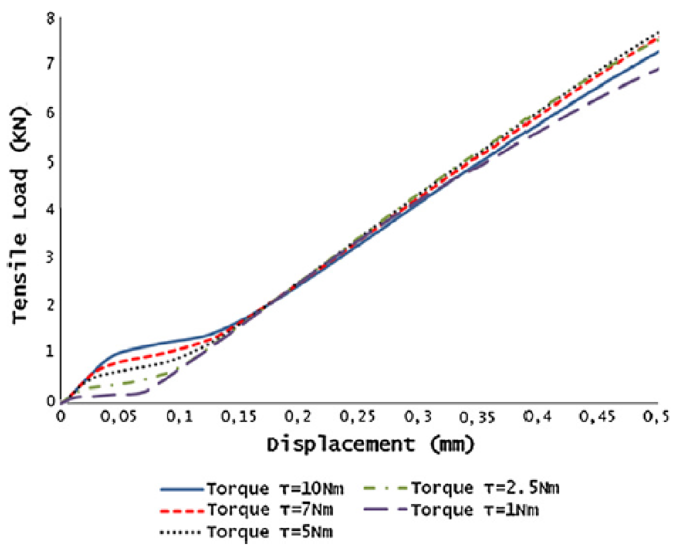


Figure 1-13: Load–displacement curves. Friction coefficient equal to 0.1. Influence of torque [27].

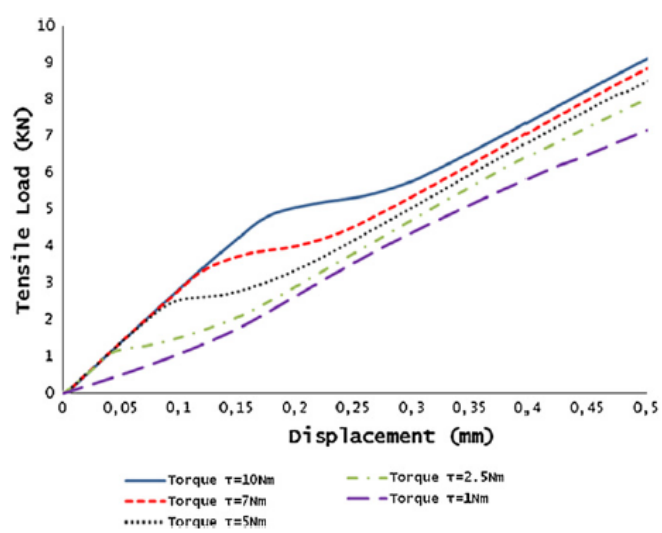


Figure 1-14: Load–displacement curves. Friction coefficient equal to 0.5. Influence of torque [27].

Girard et al. [13][14] studied the effect of clamping pressure on bearing failure of mechanically fastened carbon/epoxy laminated composite joints. Three different clamping methods were used. The first series of tests were done without any clamping pressure, using a dowel pin. The second series were carried out with a finger-tightened bolt, and the third series were carried out using a torque-tightened bolt to exert a clamping pressure of at least 20 MPa. Figure 1-15 and 1-16 show the stress vs local strain obtained by Girard et al. [13][14] for different clamping pressures. The bearing stress was defined as the load divided by the hole diameter times thickness of the laminate. Results from their studies showed that stiffness of the transversal surface is not influenced by clamping pressure. Nonetheless, the maximum stress and strain increased with clamping pressure.

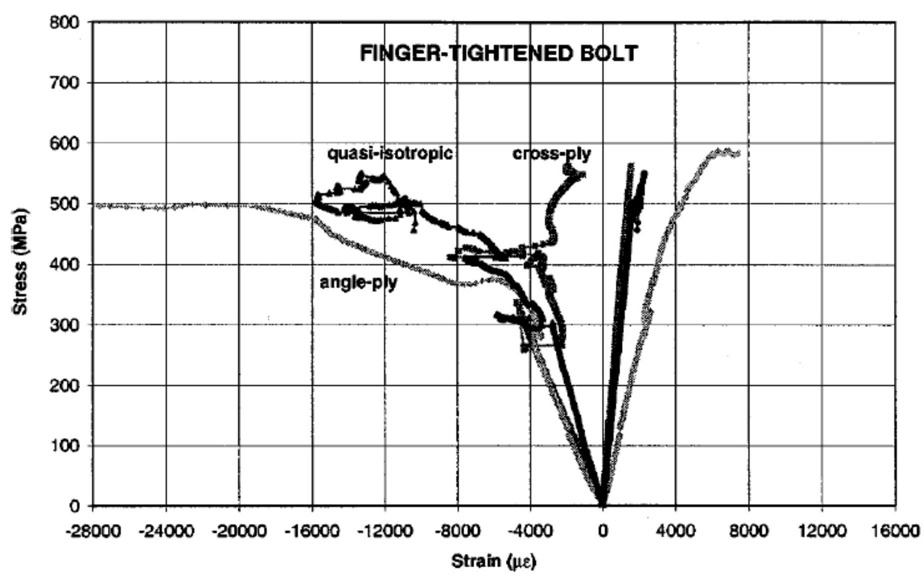


Figure 1-15: Stress vs local strain curves for finger tightened bolt [13][14].

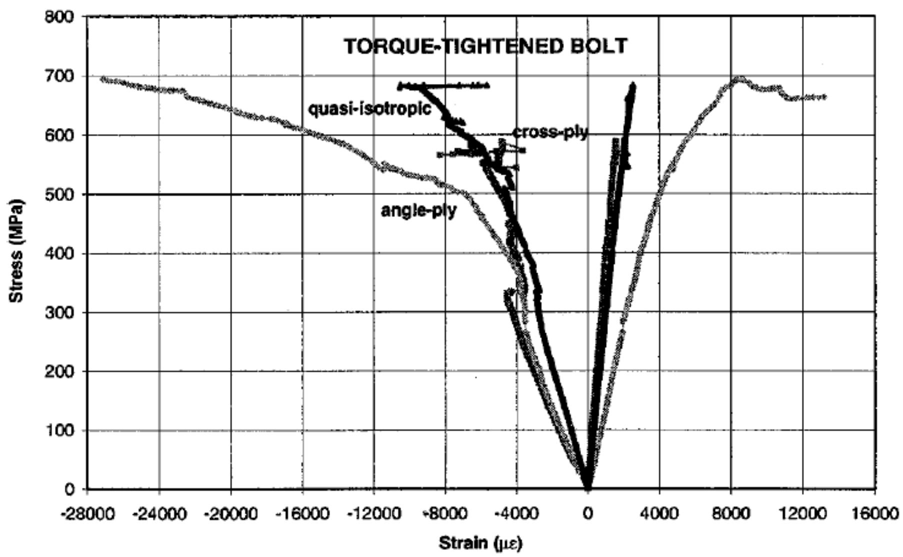


Figure 1-16: Stress vs local strain curves for 20Nm torque tightened bolt [13][14].

Khashaba et al.[28] studied the effects of torque on the strength of bolted joints in joints manufactured using glass fiber reinforced plastics (GFRP) composite laminates with 5.2 ± 0.1mm thickness. In their study, they determined the strength of bolted joints with various torques (T = 0, 5, 10, and 15 Nm) and washer sizes (outer diameter of washers, Dw = 14, 18, 22, and 27 mm). Representative results are shown in Figure 1-18. The experimental results showed that for a constant torque, the slope of the load–displacement curve (stiffness) increased with decrease in washer size. Bolted joints with 18 mm washer size and 15 Nm tightening torque manifested the maximum strength.

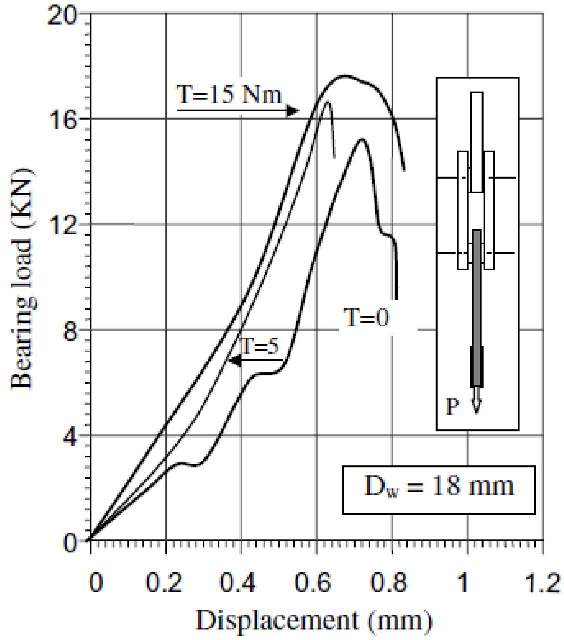


Figure 1-17: Load-displacement diagram of bolted joint with different tightening torques [28].

It was evident that for a constant bolt and washer diameters, the joint stiffness increased with increase in torque. The curve of the finger tight specimen (T = 0 Nm) showed the lowest slope (stiffness) with several knees and nonlinear curves, an indication of uneven development of internal damage. Another study showed that the bearing strength also increased with torque level as shown in Figure 1-18.

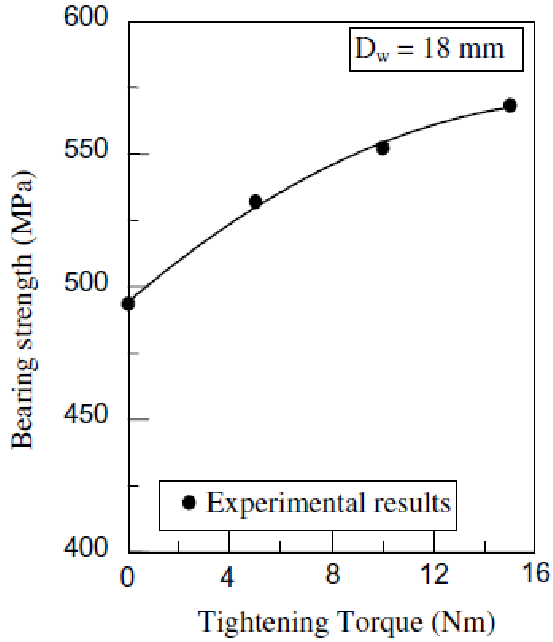


Figure 1-18: Effect of tightening torque on bearing strength of bolted joint [28].

Tong [29] also studied the effect of torque (finger tight, 6.4Nm and 12.88Nm) on carbon/epoxy composite bolted joints. His results, shown in Figure 1-18, show that the displacement increased linearly with the load until noticeable drop is seen. This behavior indicates failures such as delamination or micro buckling. Similar to other studies, the stiffness of the joint increased with increase of torque level. It was clear that the initial failure loads increased as the applied torque was increased from finger tight to 12.88 N-m. This was because of the relatively small unconstrained gap with a maximum radial clearance of 0.65 mm. Thus, the joint can still be significantly affected by the lateral constraints caused by the clamping forces applied. After initial failure, the load – displacement curves grew linearly with additional applied load but have a lower slope, meaning less stiffness.

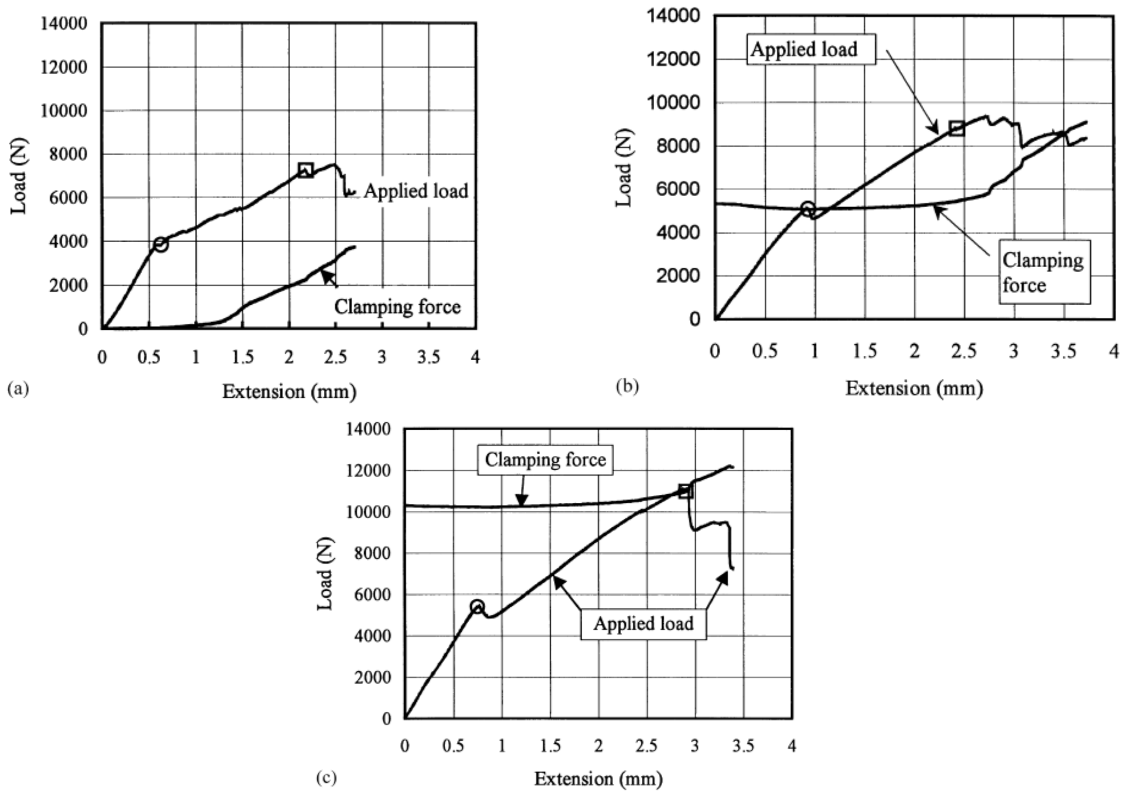


Figure 1-19: Applied load and clamping force versus the axial extension for case (a): specimen 3 with an applied torque of 0 N m (finger tight) (a); specimen 4 with an applied torque of 6.4 N m (b); specimen 8 with an applied torque of 12.88 N m (c).[29].

1.3.4. Hybrid Fastening System

One of the important parameters affecting the stiffness of bolted joints is the presence of clearances, which are inevitable to facilitate on-site assembly. Clearances reduce the stiffness and the load to initial damage of joints. Further it induces slip between the connected members, which can lead to misalignment of parts as well as the introduction of impact loads. Slip due to clearances can also cause a reduction in the fatigue life of composite bolted joints, as demonstrated in the previously cited literature[18]. In bolted joints manufactured using composite plates, the pre-tension applied on the bolts may relax due to the viscoelastic properties of the composites. The use of high-strength friction grips (HSFG) cannot be relied on for long term performance. HSFG bolts transfer the connection force between contact surfaces by friction alone. Force transmitted in this way cannot be relied on, as was shown in a preliminary study by Mottram [31]. The study showed that the bolts lost their tightness over time due to FRP relaxation.

An alternative to the close-fitted or HSFG techniques is to inject resin or resin carrying adjuncts such as metal particles into the bolt hole clearance cavity, creating what is known as a hybrid fastening system. Hybrid fastening systems with resin injected into the bolt-hole clearance offers various advantages including resistance to fatigue and shock loading, resistance to corrosion, achievement of acceptable slip and fatigue performance, and low manufacturing costs.

As mentioned above, the basic concept of the injected hybrid fastener system using resins, adhesives, or liquid carriers containing adjuncts to form structural inserts has been described in papers and patents by Cloud [6,[11][12]]

In some other hybrid joining techniques, insert-like shims are used to fill the clearance holes between the bolt and substrate. Hühne et al.[34] in their work on the effects of liquid shims on the behavior of carbon fiber laminate bolted joint showed a decrease in stiffness when the substrate thickness was reduced.

Haq et al [36] in their work showed that use of a resin insert with various reinforcements such as a carbon sleeve, a glass sleeve, or a nanoparticle filler will reduce slip and increase the load capacity and strength of composite joints while delaying delamination around the bolt holes.

1.4. Scope

In this report, single-lap joint strength using uniform substrate materials were evaluated experimentally for a novel hybrid joining technique that introduces a structural adhesive insert in the clearance between the bolt and the substrates. The effect of varying insert material and varying bolt hole clearance on the strength and performance of the resulting hybrid joints were studied.

Glass fiber reinforced polymer (GFRP) composites were used as the substrates. Bolts having a nominal diameter of ½” were used in all the cases

The test matrix incorporated 3 different insert materials and 4 different bolt radial clearances. For comparison, joint specimens with standard bolted connections having no insert and having the same clearances were tested. Figure 1-20 illustrates the joint configurations. Quantitative details of specimen design as well as the clearance and material parameters studied are given in Chapter 2 of this report.

The peak loads, displacement at peak loads, loads at initial delaminations, and slip loads were compared to assess the performance of the hybrid bolted joints. This study was intended to provide a benchmark for the better design of bolted joints using this novel hybrid joining technique.

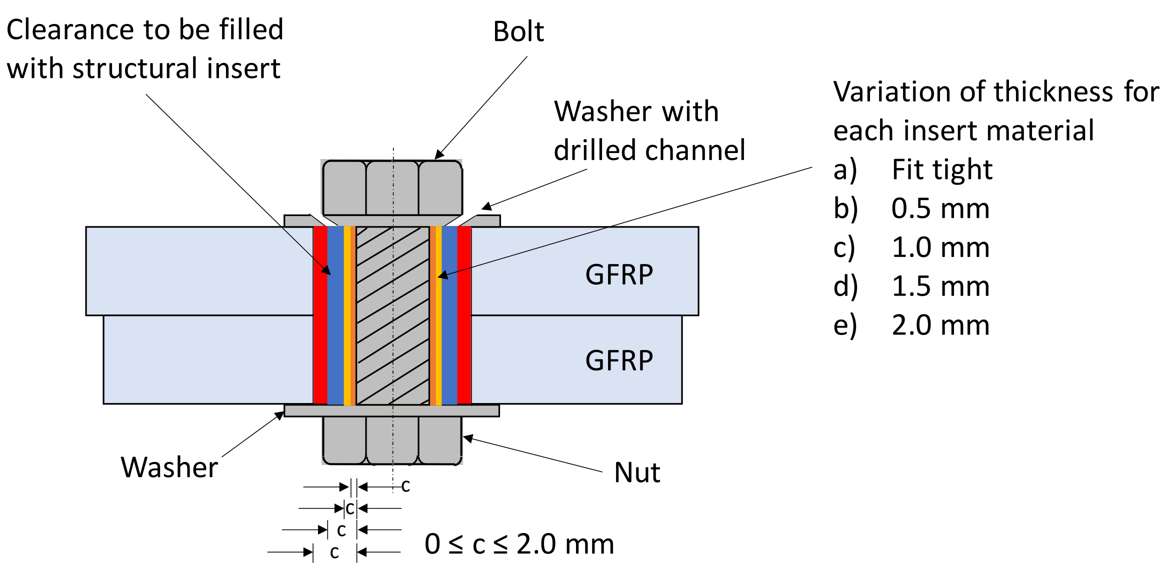


Figure 1-20. Joint configuration of hybrid fastening system for studying variations of bolt-hole clearances and insert materials.

Chapter 2: Materials and Manufacturing

2.1. Materials

The joints were made of 16-layer S-2 plain weave glass fiber reinforced plastic (GFRP) substrates, with an area-specific weight of 832 g/m^2. These substrates were bonded using PRO-SET INF-114 infusion epoxy and PRO-SET INF-210 fast infusion hardener with a mix ratio of 3.65:1 by weight. Threaded hex bolts having13 threads per inch and a bolt diameter of 0.5 inch were used in the experiment. These bolts were made of medium strength grade 5 steel. Furthermore, zinc-plated medium strength grade 5 steel hex nuts and zinc yellow-chrome plated grade 8 steel washers having 0.531" internal diameter and 1.062" outer diameter were chosen for the study. A total of three structural adhesive inserts (injected into bolt-hole clearances) namely PRO-SET INF-114 infusion epoxy, polyurethane from Scotch-Weld, and DEVCON aluminum-filled resin were used in this study.

2.2. Manufacturing of GFRP Substrate

Large plates of 16-layer GFRP were manufactured using Vacuum Assisted Resin Transfer Molding (VARTM) and then cut into substrates. A detailed description of the manufacturing process has been provided in Figure 2-1 (process diagram showing the experimental layout and layup sequence) and Figure 2-2. Initially, 16 layers of glass fabric were laid on the mold. Permeable ply was then placed over the glass fabric on both sides followed by the application of transfer media which is used to enhance the resin flow and ensure easy separation of layers to create a satisfactory surface finish. The resin was infused using three inlets, positioned such that it wetted the entire fabric. The mold was finally sealed using a vacuum bag. Tacky tape was used on the edges of the vacuum bag to ensure there was no leakage. The impregnated plate was cured at room temperature for 24 hours. The resulting thickness of the cured GFRP plate was 3/8" (9.53

mm). After room temperature curing, the plate was further cured for 8 hours at 82ºC inside a convection oven. The fiber volume fraction of GFRP was 0.55 as shown by the calculations below.

$$W_{composite} = 6979g$$

$$W_{fiber} = 5084g$$

$$W_{resin} = W_{composite} - W_{fiber} = 1895g$$

$$V_{fiber} = \frac{W_{fiber}}{\rho_{fiber}} = \frac{5084g}{2.49\,{}^{g}/{}_{cm^3}} = 2042cm^3$$

$$\frac{V_{fiber}}{V_{resin}} = \left(\frac{W_{fiber}}{W_{resin}}\right)\left(\frac{\rho_{fiber}}{\rho_{resin}}\right)$$

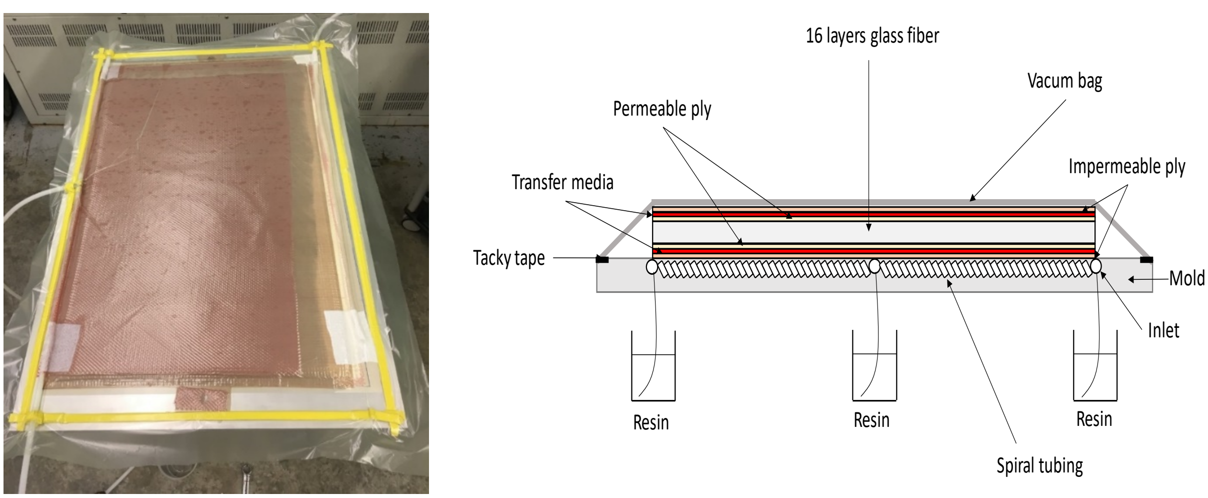
=1.23

$$V_{matrix} = \frac{1}{1 + \frac{V_{fiber}}{V_{resin}}}$$

$$= \frac{1}{1 + 1.23} = 0.45$$

$$V_f = 1 - V_{matrix} - V_{voids}$$

$$= 1 - 0.45 = 0.55$$



(a) (b)

Figure 2-1: (a) Composite (GFRP) manufacturing using VARTM process (b) Schematic of VARTM setup.

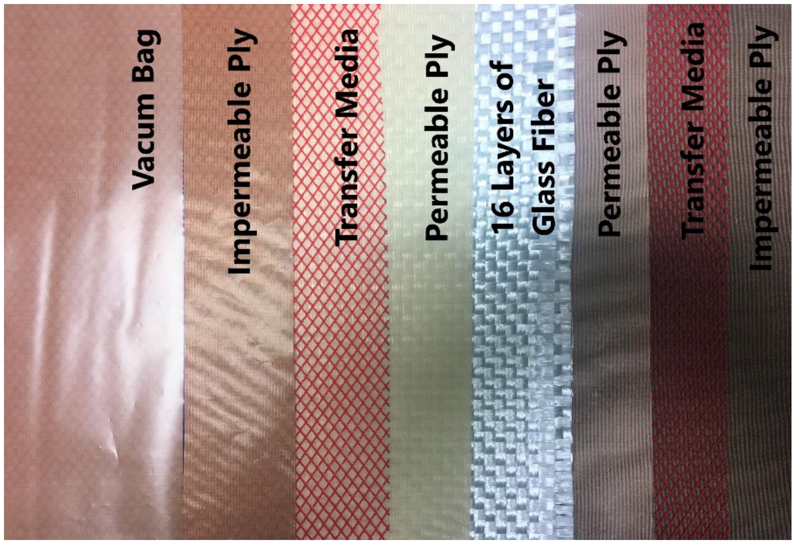


Figure 2-2: Layup for VARTM process.

2.3. Manufacturing of Hybrid Fastening System

The dimensions of the joints were designed as a function of bolt diameter (D_B) used for the experiment. Figure 2-3 shows the dimensions of the GFRP substrates. As can be seen from the figure, the edge distance (E_1) and end distance (E_2) were designated as multiples of the bolt diameter ($2.5D_B$ and $4D_B$ respectively). The specimen geometry was in conformation to the minimum requirements of bolt geometries specified in the ASCE pre-standard for pultruded (building frame) structures. The experimental program using the single lap shear bolted connection configuration is shown in Figure 2-4.

To facilitate an equal thickness of the adhesive insert around the bolt, a special polylactic centering disc was made as shown in Figure 2-5. The centering disc, which was manufactured using 3D printing, was glued to the washer to ensure central positioning of the bolt and an equal clearance around its shaft (Please see Figure 2-6). Once all joints were put together and tightened by hand, they were subjected to a preload torque of 38 ft.lb as calculated in Chapter 3. The adhesive insert was injected by drilling a channel through the washer as shown in Figure 2-7 (a). The drilling process to form the channel was very intricate and involved multiple drill sizes.

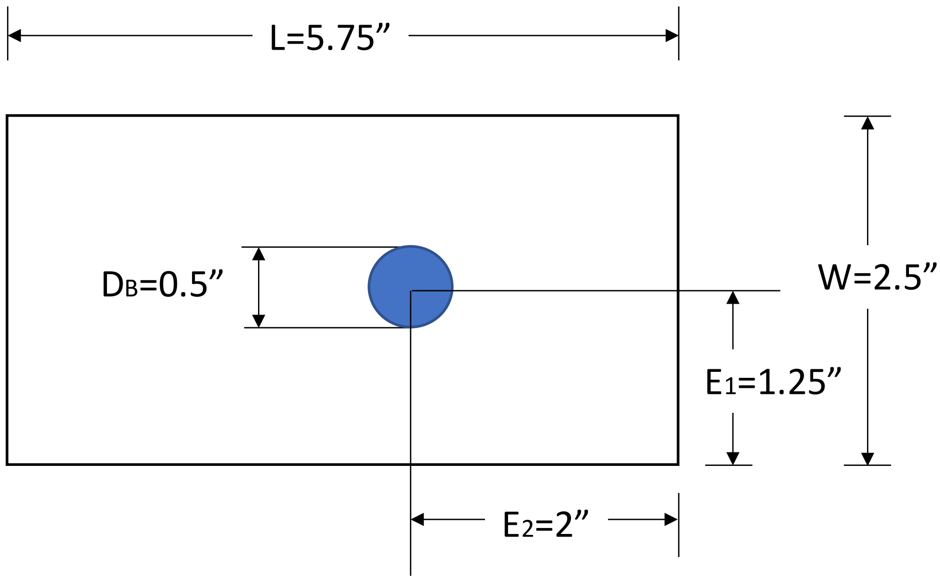


Figure 2-3: Dimension of GFRP specimen.

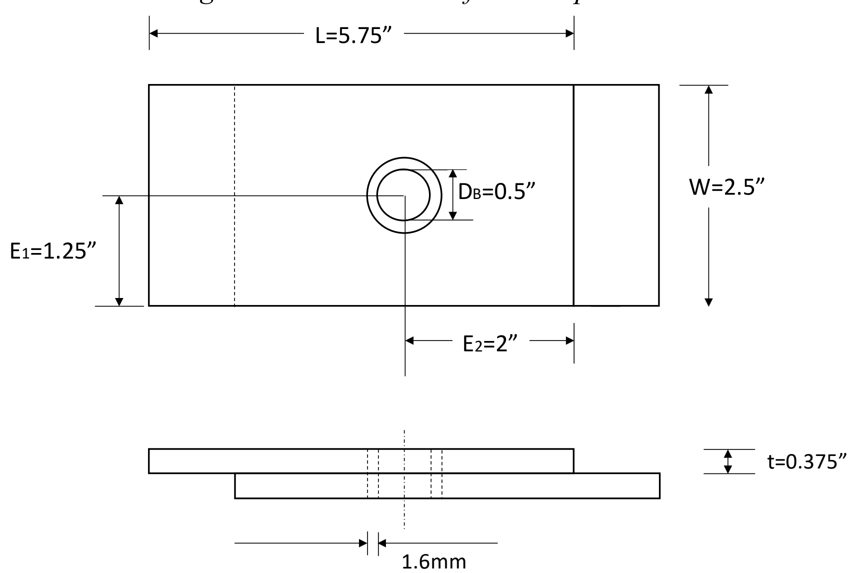
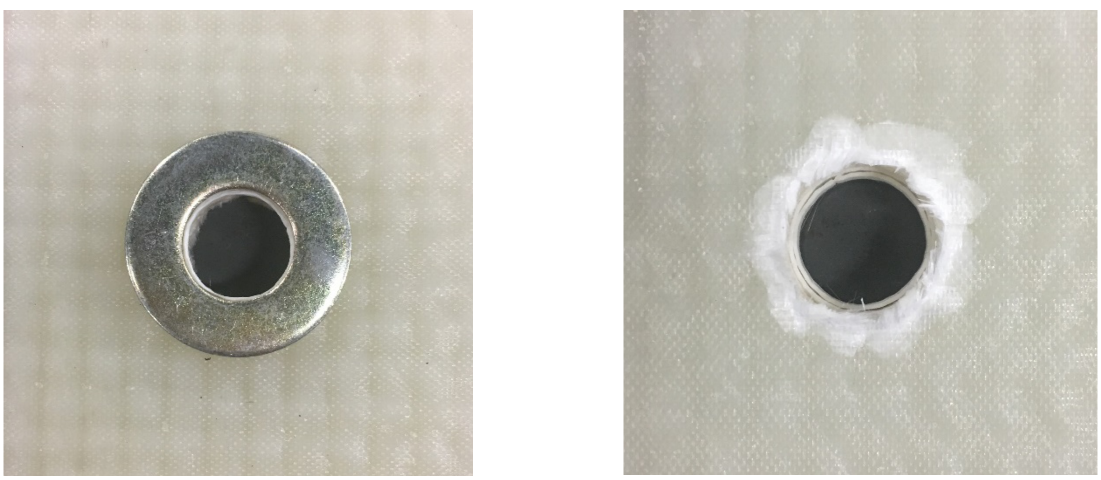


Figure 2-4: Configuration of single lap shear bolted joint specimen.

Figure 2-7 (b) shows a side view of the drilled channel through the washer. This channel was formed by using $\frac{1}{32}$" and $\frac{1}{16}$" drill bits at an angle towards the bolt. At the entry point for the resin, the channel was drilled with the larger bit. The size of this drill bit was chosen so that the hole would create an airtight seal with the head of the syringe used to inject the resin. This prevented air bubbles from entering the cavity and assured a uniform distribution of adhesive throughout. Prior to injecting the resin, a similar channel was drilled on the other side of the bolt head as an escape passage for air and excess adhesive once the cavity was completely full. This permitted an insertion for the adhesive as it was pushed through the channel by using a syringe as shown in Figure 2-8. Once the adhesive was injected into the hybrid joints, they were cured for 48 hours at room temperature.

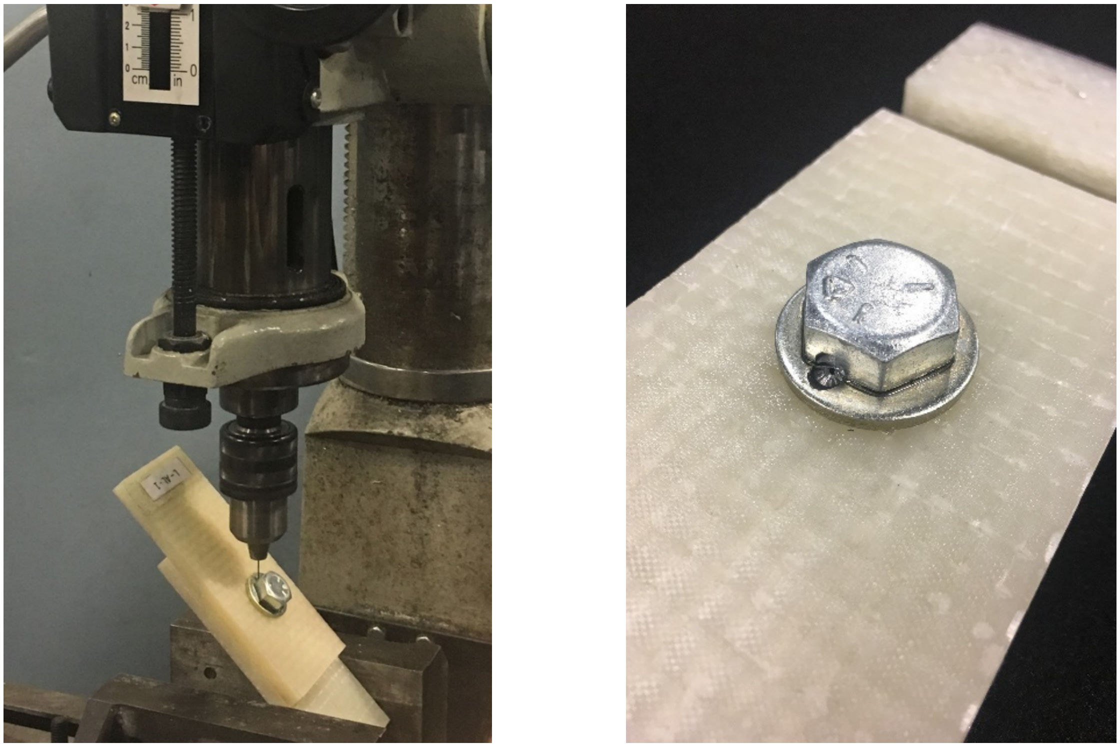
(a) (b)

Figure 2-5: *3D printed centering washer*



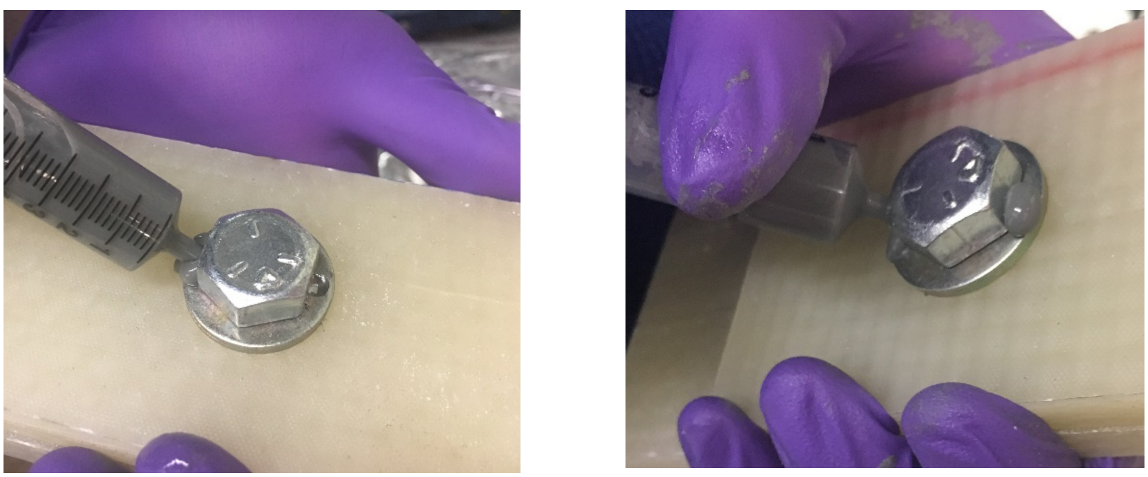
(a) (b)

Figure 2-6: Top and bottom view of centering disc attached to washer.



(a) (b)

Figure 2-7: (a) Drilling process of a small channel through the washer, (b) Sideview of drilled channel



(a) (b)

Figure 2-8: *Adhesive injection process.*

2.4. Project Approach and Parameters Studied

Experiments were carried out using multiple adhesives (detailed in section 2.1) as structural inserts as detailed in Table 2-1 below. In addition to that, specimens without any structural inserts (conventional bolted joints) were also tested to develop a baseline. For each configuration, three specimens were prepared.

Figure 2-9: Drilling process using ½" diamond core drill.

Four different bolt-hole clearances were used in this study, in accordance with ASME B18.2.8. The bolt-hole clearance for fit-class close, normal and loose were set to be around 0.5mm, 1.0mm and 1.6mm respectively for the ½" diameter bolt. Specimens with an "extra-loose" fit were added to the experimental schedule as mentioned below. For the fit tight bolted joint, the holes in the composite plates were cut using a ½" diamond core drill (Figure 2-9). For other fit-classes, holes were cut using a ½" diamond core drill first, and then the clearance was created by using cobalt steel drill bits of sizes 9/16", 17/32", 39/64" and 21/32" respectively to drill through the substrate. This procedure was performed to avoid severe delamination of the composite during drilling. Due to the drilling process, initial delamination was observed along the interior of the bolt hole as shown in Figure 2-10 (a). This delamination occurs due to the localized pushing out of the substrate layers in the vicinity of the drill bit. To ensure a smooth hole in the substrate, some of the delaminated portion was removed using a cutter as shown in Figure 2-10(b). The corresponding specimen numbering is shown in Table 2-2.


(a)

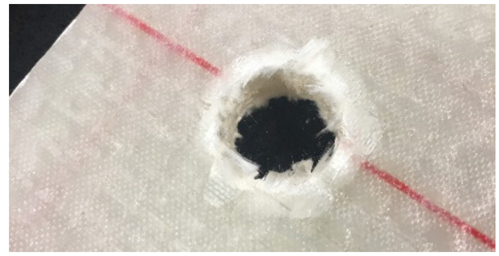

(b)

Figure 2-10:.Interlaminate delamination around bolt-hole.

Table 2-1: Clearance hole chart for inch-fasteners according to ASME B18.2.8. Also highlighted is the ½" diameter bolt used in this work and associate bolt clearances.

Clearance Holes for Inch Fasteners									
Nominal Screw Size	Fit Class - Normal			Fit Class - Close			Fit Class - Loose		
	Nominal Drill Size	Hole Diameter		Nominal Drill Size	Hole Diameter		Nominal Drill Size	Hole Diameter	
		Min.	Max.		Min.	Max.		Min.	Max.
#0	#48	0.076	0.082	#51	0.067	0.071	3/32	0.094	0.104
#1	#43	0.089	0.095	#46	0.081	0.085	#37	0.104	0.114
#2	#38	0.102	0.108	3/32	0.094	0.098	#32	0.116	0.126
#3	#32	0.116	0.122	#36	0.106	0.110	#30	0.128	0.140
#4	#30	0.128	0.135	#31	0.120	0.124	#27	0.144	0.156
#5	5/32	0.156	0.163	9/64	0.141	0.146	11/64	0.172	0.184
#6	#18	0.170	0.177	#23	0.154	0.159	#13	0.185	0.197
#8	#9	0.196	0.203	#15	0.180	0.185	#3	0.213	0.225
#10	#2	0.221	0.228	#5	0.206	0.211	B	0.238	0.250
1/4	9/32	0.281	0.290	17/64	0.266	0.272	19/64	0.297	0.311
5/16	11/32	0.344	0.354	21/64	0.328	0.334	23/64	0.359	0.373
3/8	13/32	0.406	0.416	25/64	0.391	0.397	27/64	0.422	0.438
7/16	15/32	0.469	0.479	29/64	0.453	0.460	31/64	0.484	0.500
1/2	9/16	0.562	0.572	17/32	0.531	0.538	39/64	0.609	0.625
5/8	11/16	0.688	0.698	21/32	0.656	0.663	47/64	0.734	0.754
3/4	13/16	0.812	0.824	25/32	0.781	0.789	29/32	0.906	0.926
7/8	15/16	0.938	0.950	29/32	0.906	0.914	1-1/32	1.031	1.051
1	1-3/32	1.094	1.106	1-1/32	1.031	1.039	1-5/32	1.156	1.181
1-1/8	1-7/32	1.219	1.235	1-5/32	1.156	1.164	1-5/16	1.312	1.337
1-1/4	1-11/32	1.344	1.360	1-9/32	1.281	1.291	1-7/16	1.438	1.463
1-3/8	1-1/2	1.500	1.516	1-7/16	1.438	1.448	1-39/64	1.609	1.634
1-1/2	1-5/8	1.625	1.641	1-9/16	1.562	1.572	1-47/64	1.734	1.759

Table 2-2: Specimen Nomenclature Used.

Adhesive Insert Material → / **Clearance Size ↓**	**Proset Epoxy**	**Polyurethane**	**Aluminum Liquid**	**Conventional (without insert)**
Fit Class - Close	C – P - 1	C – PU - 1	C – AL - 1	C – N - 1
	C – P - 2	C – PU - 2	C – AL - 2	C – N - 2
	C – P - 3	C – PU - 3	C – AL - 3	C – N - 3
Fit Class - Normal	N – P - 1	N – PU - 1	N – AL - 1	N – N - 1
	N – P - 2	N – PU - 2	N – AL - 2	N – N - 2
	N – P - 3	N – PU - 3	N – AL - 3	N – N - 3
Fit Class - Loose	L – P - 1	L – PU - 1	L – AL - 1	L – N - 1
	L – P - 2	L – PU - 2	L – AL - 2	L – N - 2
	L – P - 3	L – PU - 3	L – AL - 3	L – N - 3
	L – P - 4	L – PU - 4	L – AL - 4	L – N - 4
Fit Class – Extra Loose	XL – P - 1	XL – PU - 1	XL – AL - 1	XL – N - 1
	XL – P - 2	XL – PU - 2	XL – AL - 2	XL – N - 2
	XL – P - 3	XL – PU - 3	XL – AL - 3	XL – N - 3

Table 2- 2 enumerates all the joint samples in this work for varying clearances and insert material type. The nomenclature used is provided in equation (1) as follows:

$$A - B \text{ - } \# \tag{1}$$

wherein ‘A’ represents the clearance type, ‘B’ represents the insert material type and ‘#’represents the specimen number. As explained in chapter 2, four clearances were studied, and hence parameter A in equation 1 has four values namely (i) close-fit (C), (ii) normal-fit (N), (iii) loosee-fit (L) and (iv) extra-loose fit (XL). Similarly the parameter B has four values corresponding to the insert material type, namely: (i) Proset epoxy (P), (ii) Polyurethane (PU), (iii) Aluminum filled epoxy (AL), and (iv) normal/conventional joint without an insert (N). The next chapters focus on the experimental testing and results from the characterization of all the joint specimens enumerated in Table 2- 2.

Chapter 3: Experimental Method & Approach

This chapter discusses the experimental setup, torque applied to the bolts and associated calculations, and the definition of parameters to compare the results of the various case studies performed in this work.

3.1. Experimental Testing Parameters and Torque Calculations

The final phase in the manufacturing process of conventional joints is the application of torque load. As mentioned, the clamping load in a joint that is developed by the bolting torque is critical to its performance. Clamping force was not selected as a variable parameter in this study, so a single value of bolting torque was selected on the basis of standard design practice. The bolting torque was calculated using the following equation and procedure.

$$T = KPD \qquad \text{Equation (1)}$$

where,

T = Torque (ft.lbs)

K = Coefficient of friction

P = Desired clamp load tension (lbs)

D = Nominal diameter (inches)

In this study, grade 5 bolts of diameter ½'' and coarse thread of 13tpi were used. The torque load was calculated using equation 1 in accordance with the design tables provided by the bolt manufacturer [26]. This torque was further reduced by 33% as the joints were tested in shear. Table 2- 1 shows the comparison of the torque calculation for grade 2 and grade 5 bolts based on the design table and Equation 1.

Table 3-1: Calculation of maximum torque for different bolt grades (grade 2 & grade 5).

	GRADE 2	**GRADE 5**
Design Table	From table provided by manufacturer T = 49 ft.lbs Adjustments to torque setting based on thread treatment, for cadmium plating reduce 25% T = 36.75lbs (reduced torque 33% for bolt in shear); T = 25 ft.lbs	From table provided by manufacturer T = 75 ft.lbs Adjustments to torque setting based on thread treatment, for cadmium plating reduce 25% T = 56.25lbs (reduced torque 33% for bolt in shear); T = 38 ft.lbs
Calculation	$A_s = 0.1419\text{in}^2$ $S_t = 55000\text{psi}$ $P = 0.1419\text{x}0.75\text{x}55000$ $= 5853.375\text{lb}$ $T = KPD$ $= \frac{0.20 \text{ x } 5853.375\text{lb x } 0.5\text{inch}}{12\text{inch}} \text{x ft}$ $= 49\text{ft. lb}$ (Adjustments to torque setting based on thread treatment, for cadmium plating reduce 25% $T = 36.75\text{ft. lb}$ (reduced torque 33% for bolt in shear); $T = 25\text{ft. lb}$	$A_s = 0.1419\text{in}^2$ $S_t = 85000\text{psi}$ $P = 0.1419\text{x}0.75\text{x}85000$ $= 9046.125\text{lb}$ $T = KPD$ $= \frac{0.20 \text{ x } 9046.125\text{lb x } 0.5\text{inch}}{12\text{inch}} \text{x ft}$ $= 75\text{ft. lb}$ (Adjustments to torque setting based on thread treatment, for cadmium plating reduce 25% T = 56.25lbs (reduced torque 33% for bolt in shear); T = 38 ft.lbs

Based on the thread treatment, the torque setting was reduced by 25%, and the maximum torque considered in this study was 38 ft.lbs.

Prior to injecting the resin, the bolts were preloaded to the torque level as outlined above. After resting injection, all the specimens were then cured for 48 hours before being tested. Samples 'L – P - 2, L – PU - 2, L – AL - 2 and L – N – 2' were selected to be cut using a metal cutting bandsaw as shown in Figure 3- 1. This was done to observe the cross-sectional view showing the bolt and clearances filled with the adhesive. This was done to ensure that the assembly process was not introducing any air-bubbles or voids in the clearance cavity. The assembled joints were then quasi-statically tested in tensile-shear configuration as described in the next section

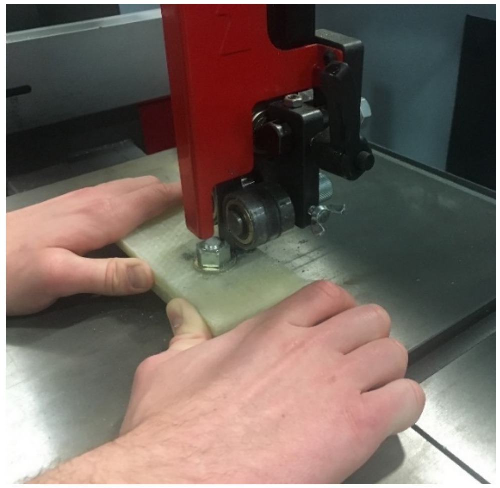
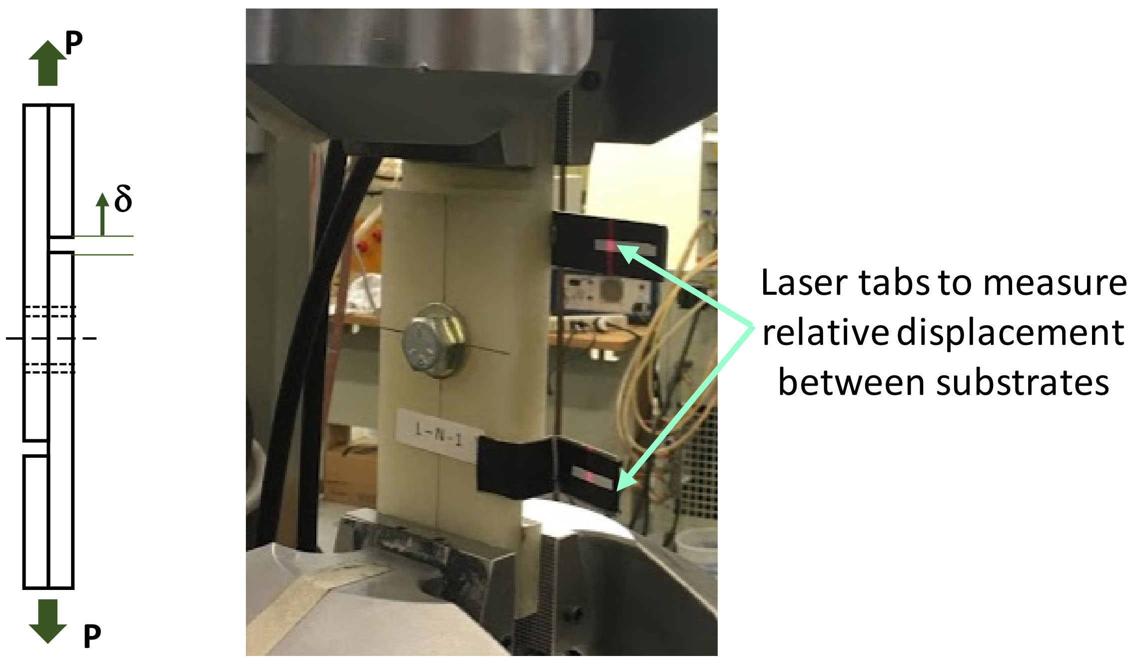


Figure 3-1: Process of cutting the cross section of bolted joints/



(a) (b)

Figure 3-2: (a) Schematic of Test setup and (b) actual test setup.

3.2. Experimental Test Setup

Blocks of similar material and dimensions as the substrates were attached to the assembled joints in the grip-locations where the joints are clamped in the MTS and loads are applied. This ensures that the joint is tested in pure shear configuration. The testing was performed using a uniaxial testing machine (MTS 810) with a load cell capacity of 100 kN. A loading rate of 5 mm/min was maintained for all joints, and they were tested until failure. An external laser extensometer was used to measure the relative displacements between the substrates in addition to the MTS crosshead displacement. The schematic of testing and actual test setup is shown in Figure 3- 2.

3.3. Parameter Definitions to Compare Joint Performance

The performance of the hybrid fastening system was compared to conventional joints with similar clearances. A schematic of typical load - displacement responses of conventional and hybrid joints is provided in Figure 3- 3.

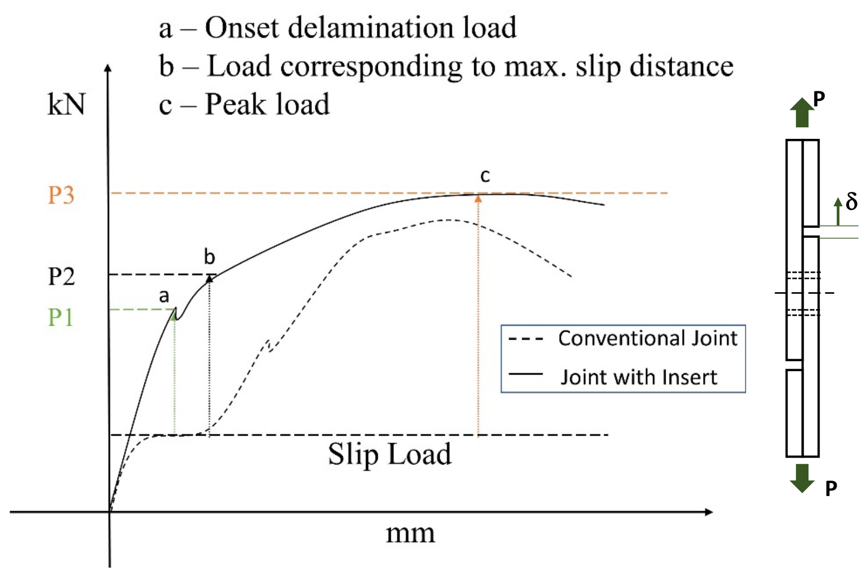


Figure 3-3: Schematic of lap-shear behavior of conventional and hybrid joints.

From Figure 3- 3, it is obvious that the conventional joint experiences a bolt-adherend slip characterized by a sudden increase in displacement without any significant increase in load. In applications wherein small displacements are important, this bolt-adherend slip can be considered as the failure of the resulting joint. The load corresponding to this bolt-adherend slip is termed as the 'Slip-load.' The maximum displacement occurring due to this bolt-adherend slip prior to joint re-alignment to carry load is termed as the "maximum slip displacement." It should be noted that all the hybrid joints tested in this work did not experience any bolt-adherend slip, thereby the term "slip load" is exclusively representative of conventional bolted joints. In hybrid joints, the first sign of failure is in the form of a small drop in load corresponding to onset/start of delamination. The load corresponding to this point is termed as the "Onset of Delamination Load (ODL)." It should be noted that the onset of delamination also occurs in conventional joints after the occurrence of bolt-adherend slip. Finally, the maximum load experienced by the joint is termed as the "Peak load (PL)."

Since 'slip load' in conventional joints is considered the 'failure criterion,' three parameters were framed to compare the performance of hybrid joints. The definitions of these three parameters are provided as follows.

3.3.1. Parameter – 1 (P_1): Comparing Onset of Delamination in Hybrid joints with Slip Load

Parameter – 1 (P_1) is defined as the ratio of 'the load at onset of delamination in hybrid joints' to 'the slip load of conventional joints with equivalent clearance' and is represented in equation (2).

$$P_1 = \frac{Onset\_Delamination\_Load_i}{SlipLoad\_Equival\_Clearance} = \frac{ODL}{SL_{equiv\_clearance}} \qquad \text{Eq. (2)}$$

The load corresponding to P_1 is represented in Figure 3- 3 with the letter 'a'. P_1 quantifies the performance of hybrid joints relative to slip loads of conventional joints. In other words, (P_1 =

1) indicates that the slip load and the load at onset of delamination of hybrid joints are the same. Similarly, (P_1>1) will indicate that the hybrid joints have onset of delamination loads higher than the slip load. Lastly (P_1<1) will indicate the hybrid joints having onset of delamination at loads lower than the occurrence of slip loads.

3.3.2. Parameter – 2 (P_2): Comparing Load at Maximum Slip Displacement in Hybrid Joints with Slip Loads in conventional Joint

Parameter – 2 (P_2) is defined as the ratio of the 'load in hybrid joints corresponding to the maximum slip displacement in equivalent conventional joints' to 'the slip load of conventional joints with equivalent clearance,' and is represented by equation (3).

$$P_2 = \frac{Load\_Corresponding\_Max\_Slip_i}{Control\_Joint\_SlipLoad\_Equival\_Clearance} = \frac{Load@Max\_SlipDisp\_i}{SL_{equiv\_clearance}} \qquad \text{Eq. (3)}$$

The load corresponding to P_2 is represented in Figure 3- 3 with a letter 'b'. In applications where displacement is critical, P_2 provides the load carrying capacity of hybrid joints at displacements corresponding to the maximum slip in conventional joints. This parameter P_2 is thus not valid for conventional joints and only valid for comparing hybrid joints with equivalent conventional joints. P_2 will always be greater than 1.

3.3.3. Parameter – 3 (P_3): Comparing Peak Loads in Hybrid joints with Slip Load

Parameter – 3 (P_3) is defined as the ratio of the "peak load in hybrid joints" to the "slip load in conventional joints of equivalent clearance" and is represented in by equation 4.

$$P_3 = \frac{Peak\_Load_i}{Control\_Joint\_SlipLoad\_Equival\_Clearance} = \frac{Peak\_Load}{SL\_control\_ec} \qquad \text{Eq. (4)}$$

The load corresponding to P_3 is represented in Figure 3- 3 with a letter 'c'. P_3 will always be greater than 1, as the peak loads are higher than the slip loads. The next two chapters cover the experimental results corresponding to the varying insert materials and hole clearances.

Chapter 4: Effect of Varying Insert Material (Constant Clearance, 1.5 mm.) on the Efficiency of Hybrid Fastening System

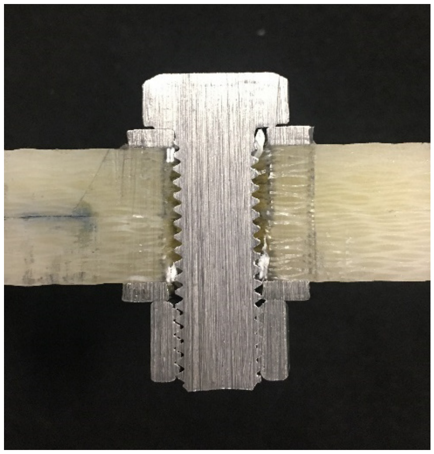
4.1. Introduction

The work on hybrid fastened joints similar to the that performed in this thesis, wherein an adhesive structural insert is used to fill the cavity/gap between the bolt and the adherend is limited to the work performed in the research group of Prof. Haq and Prof. Cloud. In an earlier work [35], an SC-15 epoxy was used as an adhesive structural insert in a hybrid joint consisting of glass fiber reinforced plastic (GFRP) substrates, ½" diameter grade 5 bolt, and a constant clearance of ~1.5 mm. The insert material and the clearances were kept constant in this work [35]. It is prudent to compare our study on the same clearance (1.5 mm) with the earlier work [35]. Hence, this chapter compares the effect of insert materials for a constant clearance of 1.5 mm (loose-fit).

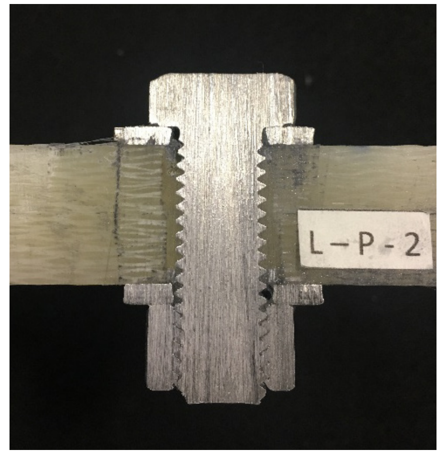
Figure 4 - 1shows the cross section of loose-fit (1.5 mm) hole clearance bolted joints for both the conventional and the hybrid fastening system for each of the adhesive inserts used in this study. It can be observed from the figure that the cavity between bolt shank and hole was completely filled by the insert material. Air-voids or improper filling was not observed indicating a good manufacturing process.

4.2. Performance of a Conventional Bolted Joint

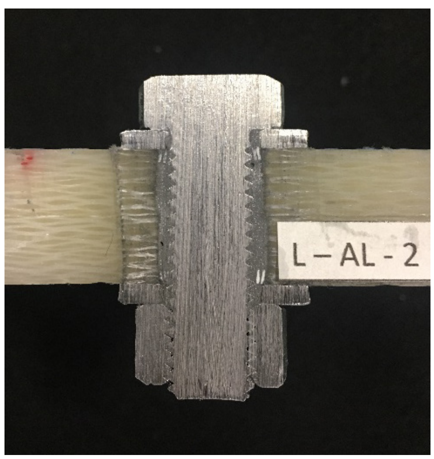
Figure 4-2 shows the representative load-displacement response of conventional bolted joint with loose-fit (1.5 mm) clearance. As explained in section 3.3, the joint is tested in shear loading. When the compressive forces and associated friction forces due to the application of the torque are overcome by the applied shear load, a bolt-adherend slip is observed. The corresponding average slip load for these samples was ~8 kN. In the slip event, the load does not significantly increase, but the displacement increases until the bolt tilts and is resting/bearing on the substrates.



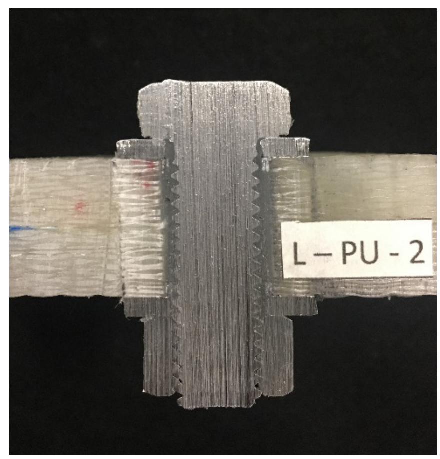
(a) Conventional joint



(b) Hybrid joint with PRO-SET epoxy



(c) Hybrid joint with aluminum liquid



(d) Hybrid joint with polyurethane

Figure 4-1: Cross section of bolted joints with 1.5 mm clearance.

Further increase in applied load results in onset of delamination in the GFRP substrates at the locations of contact of the bolts with the substrates. Delamination and fiber breakage at bolt substrate contact surfaces are represented by a small drop in the load displacement curves. This is followed by a reduction in stiffness until the peak load is reached. After the slip-load, the bolt-shank undergoes a combination of bending and shear loads. As the load increases the delamination increases until the peak load is reached. Beyond the peak load, the extent of delamination increases with increase in displacement and reduction in load carrying capacity.

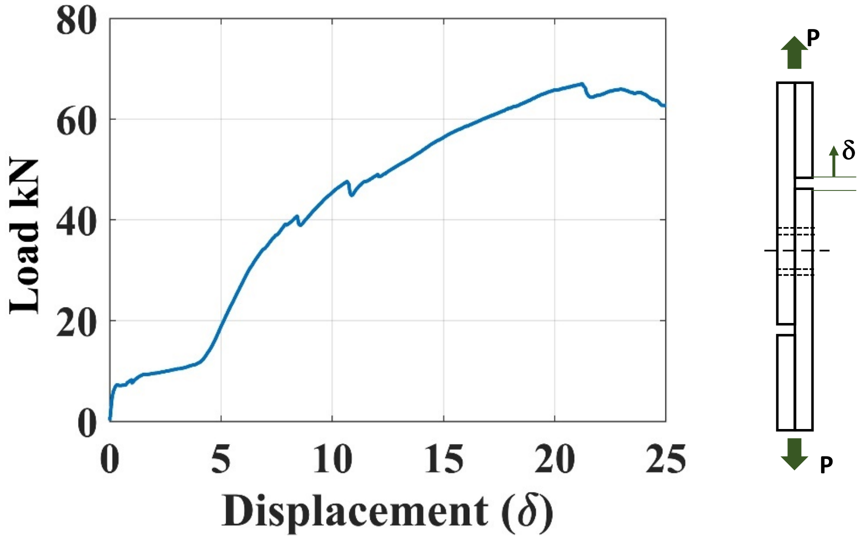


Figure 4-2: Representative Load-displacement response for conventional bolted joint (specimen L-N).

Figure 4-3 shows the post failure images of conventional bolted joints. Severe delamination was observed in the substrate around the bolt-hole along with plastic deformations in the washers. This can be attributed to the bearing load introduced by the bolt on the hole surface. The dominant mode of final failure was bolt pull-through in all the samples of this case (L-N-#).

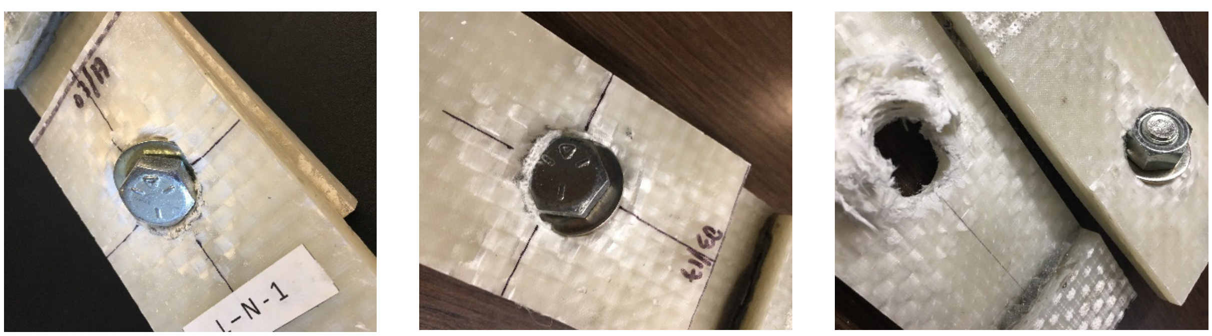


Figure 4-3: Post failure images of conventional bolted joints.

4.3. Effect of Insert Material on Hybrid Joints with 1.5 mm bolt-hole clearance(L-N-#)

Figure 4-4 shows the representative load-displacement response of each of the hybrid joints corresponding to the three different structural insert material. For comparison, the response of the conventional joint without any insert material is also included.

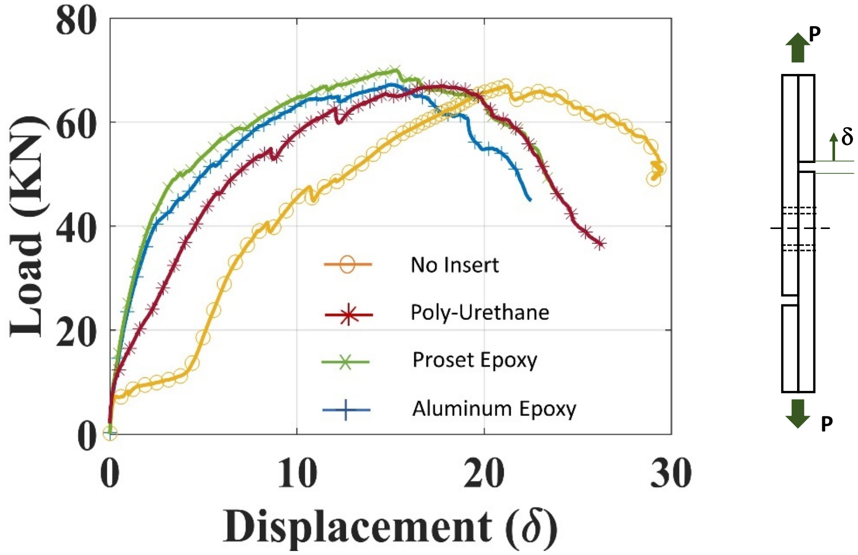


Figure 4-4: Load-displacement response for hybrid fastening system with various structural inserts (bolt-clearance = 1.5 mm.)

As explained in section 3.3, bolt-adherend slip was not observed in any of the hybrid joints tested in this case study and is shown in Figure 4-4. However, for joints with polyurethane (ductile, low-stiffness) insert, a reduction in stiffness was observed in the loading region equivalent to the slip load in conventional joint. This shows that the insert material is activated after the slip load and acts as a structural element to transfer the load from the substrate to the bolt and *vice-versa*, The onset of delamination loads of joints with SC-15, Aluminum-filled epoxy and Proset epoxy are approximately 5.5 times better than the slip loads of the conventional joints. The joints with polyurethane inserts showed an improvement of 5 times better properties than conventional joints.

Figure 4-5 compares the parameters P_1, P_2 and P_3 (defined in section 3.3) for the three insert materials in this work and the SC-15 epoxy from earlier work [35]. P_1, P_2 and P_3 represent the delamination onset load, the load corresponding to the maximum slip displacement and the peak load relative to the slip load of conventional joints (section 3.3). It is evident that the hybrid joints with all the four inserts outperformed the conventional joints.

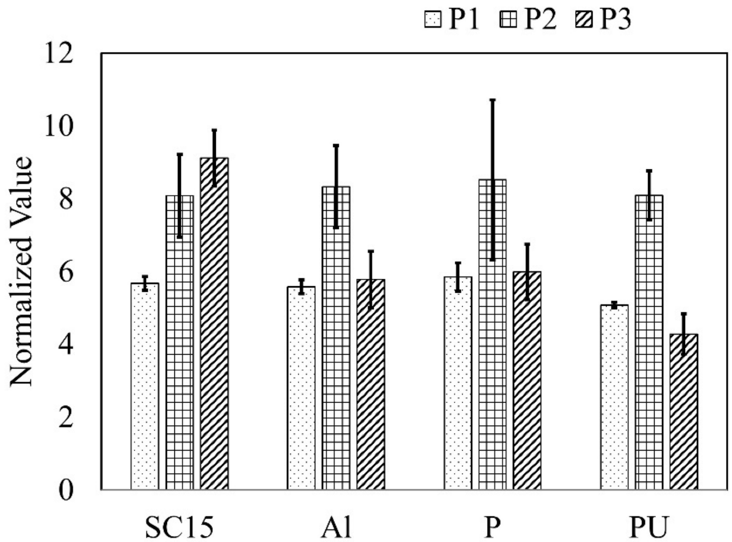
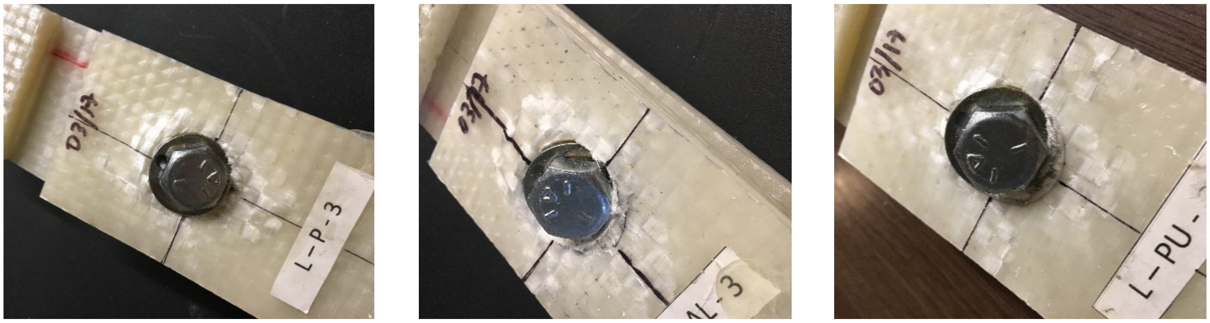


Figure 4-5: Effect of different insert material on constant clearance (1.5 mm).

P_2 (load corresponding to the maximum slip displacement in equivalent control) parameter showed an average improvement of ~8 times that compared to that of the slip-loads of conventional joints. Interestingly, the parameter P_2 was statistically constant for all the insert materials in this work. This indicates that while the bolt-adherend slip is eliminated by the presence of adhesive insert, the stress-transfer from the bolt to the substrates is efficient for all insert materials. Hence, the loads corresponding to onset of delamination are the same for all the hybrid joints.

Hybrid joints with SC-15 as structural insert showed the highest P_3 (representation of peak loads) values of all joints tested in this case study. This can be attributed to change not only in the insert material but also in the substrate. In the earlier work, the substrates were also made of SC-15 along with the insert material. SC-15 is a two-part epoxy with an additional toughening agent and thereby has higher performance compared to the inserts used in this work.

Figure 4-6 shows the extent of failure in hybrid joints with different adhesive insert materials. Compared to the conventional bolted joints (see Figure 4-3), the extent of damage in joints with structural inserts was relatively minimal and bolt pull-through was not observed.



(a) (b) (c)

Figure 4-6: Post failure images of hybrid fastening system (a) Proset epoxy (b) Aluminum epoxy (c) Poly-Urethane.

4.4. Chapter Conclusion

In this chapter, the effect of insert material was studied for hybrid joints with a constant clearance of 1.5 mm (loose-fit). Bolt-adherend slip was eliminated in all the hybrid joints. Depending on the insert material, the performance of the hybrid joints could be tailored. Polyurethane insert joints had lower stiffness but higher ductility. On average, the performance (P_1, P_2, P_3 combined) of all hybrid joints was ~ 4-8 times higher/better than the slip loads of the equivalent conventional bolted joint. Additionally, the extent of damage in hybrid joints was less severe relative to the conventional joints. Similar comparisons for the effects of insert material can be made for other constant clearances in this study. For brevity, those are not included and instead, the effect of clearance on the efficiency of hybrid joints is discussed in detail in the next chapter.

Chapter 5: Effect of Varying Bolt Hole-Hole Clearance on the Efficiency of Hybrid Fastening System

This chapter showcases the results of the experimental characterization of the hybrid bolted joints with varying bolt clearances. As described in section 2.4, four different bolt-hole clearances were studied for each of the insert materials. These bolt-hole clearances were characterized as close fit (C, 0.5mm), normal fit (N, 1.0mm), loose fit (L, 1.5mm) and extra loose fit-class (XL-2.0mm). The aforementioned bolt-clearances are shown in Table 5-1.

Table 5-1: Bolt-adherend Clearance Characteristics.

Clearance Type / Fit-Class	Designation/ Symbol used	Clearance size (mm.)
Close	C	0.5
Normal	N	1.0
Loose	L	1.5
Extra Loose	XL	2.0

In the following sections, the effect of bolt hole clearance on conventional joints and each of the insert materials are presented and discussed.

5.1. Effect of Bolt-hole Clearance on Conventional Joints

Figure 5-1 shows the representative load-displacement responses of the conventional bolted joints corresponding to each of the bolt-hole clearance studied int his work. The initial segment in the load-displacement curve reveals a linear-elastic behavior up to ~10kN for all joints. At this point, a bolt-substrate slip occurs in all joints. As explained in the previous chapter, the compressive force holding the joints together is provided by the torque/clamping load applied on the joint. When the sliding forces (applied) loads are greater than this compressive force, the bolt-adherend slip occurs. Since the torque was maintained a constant for all joints in this work, the slip loads remain approximately constant for all joints. But, the maximum slip displacement is controlled by the bolt-hole clearance. The higher the clearance values, the more the slip displacement. This maximum slip distance is the distance at which the bolt comes into contact (bearing) onto the substrates to an extent that it can transfer the applied loads. At the end of the slip phase, the value of the load increases linearly until the onset of delamination in the composite substrates. These are progressive delamination's, and they can further reduce the stiffness. As the applied load increases, the peak load is achieved, after which a rapid increase in delamination/failure with a continuous drop in load is observed.

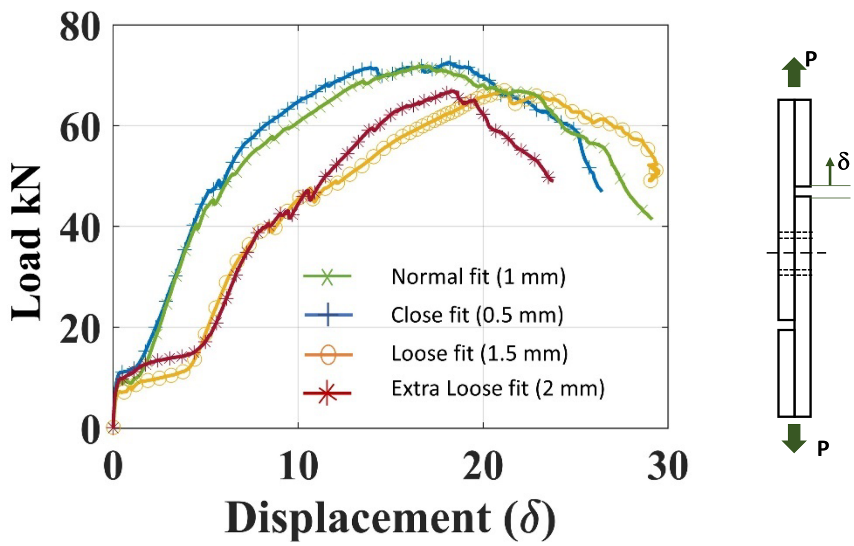


Figure 5-1: Load-displacement response of conventional bolted joint (without insert) for varying bolt-hole clearances.

Figure 5-2 shows the comparison of parameters P_1 (onset of delamination) and P_3 (Peak load) as a function of bolt-hole clearance for conventional joints. It should be noted that parameter P_2 compares the load in hybrid joints at the maximum slip loads to its corresponding slip load in conventional joint. Hence this parameter P_2 does not apply for conventional bolted joints and is not shown in Figure 5-2. For parameter P_3, it is evident that the best properties were obtained for joints with normal (1 mm) and loose (1.5 mm) clearances. This suggests that there is a need for an optimal clearance in GFRP substrates to not only efficiently transfer the loads but also to mitigate the progression of failure. For instance, in extra loose clearances, upon bolt-adherend slip there will be a considerable tilt/rotation of the bolt along with locations of high-stress concentration where the bolt is resting/bearing on the GFRP substrate. This will lead to early onset of delamination (P1) and low peak loads (P3), and was observed in this case as shown in Figure 5-2.

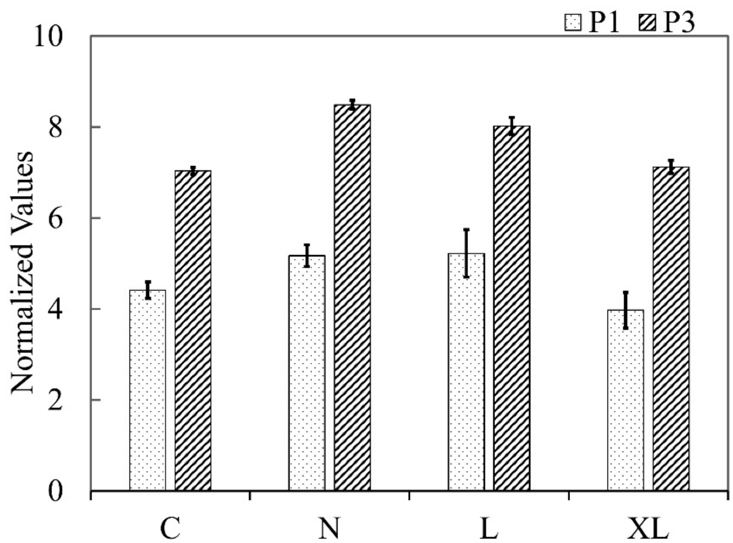
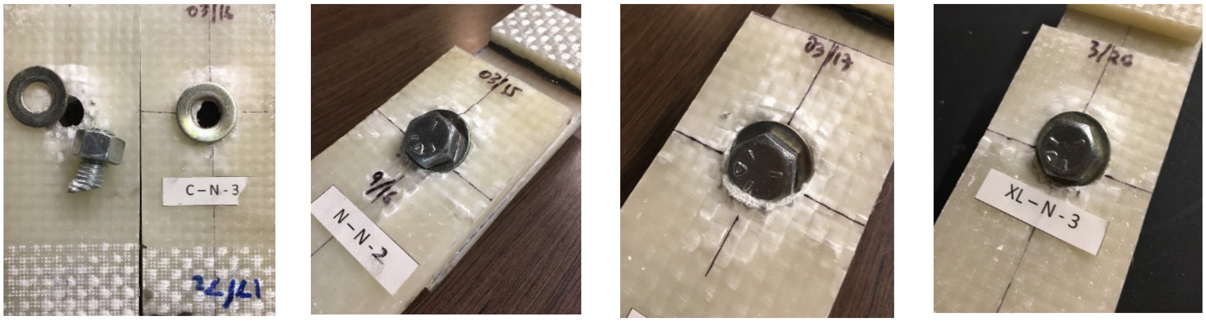


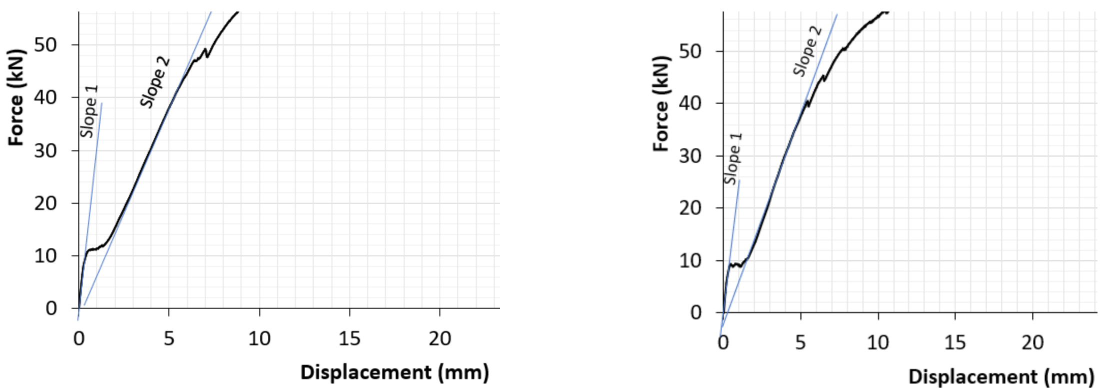
Figure 5-2: Effect of clearance on conventional joints (no inserts).

Figure 5-3 shows the post-failure images of conventional bolted joints having different bolt-hole clearances. It is clear that the mode of failure changes with respect to bolt-hole clearance. When the clearance is small, there is not enough space for the bolt to tilt or rotate, and it experiences pure shear leading to bolt fracture. When the clearance increases, the bolt tilts/rotates and experiences a combination of bending and shear along with stress-concentrations at the bearing points. Hence the delamination continues at the bearing points until the bolt is pulled out of the joint.

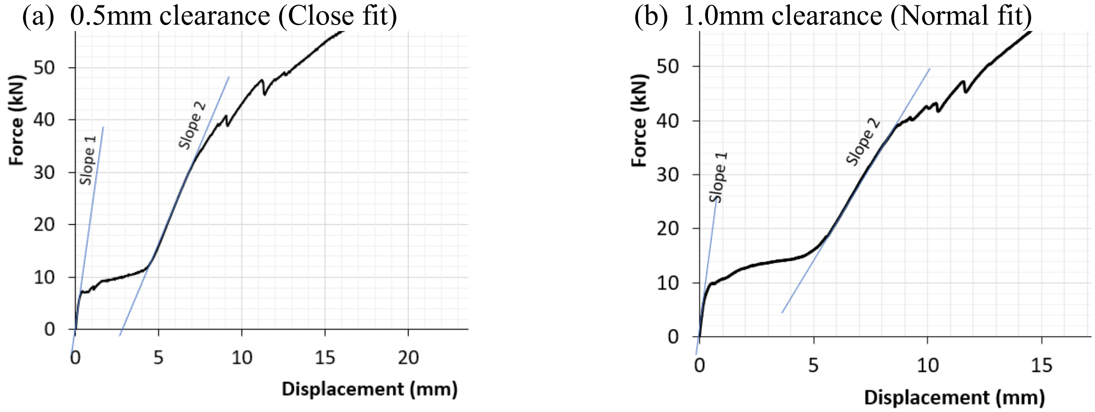


(a) *Close fit (0.5mm),* *(b)* *Normal fit (1.0 mm)* *(c)* *Loose fit (1.5mm)* *(d)* *Extra loose fit (2 mm)*

Figure 5-3: Post failure images of conventional bolted joints at various clearances.



(a) 0.5mm clearance (Close fit) (b) 1.0mm clearance (Normal fit)



(c) 1.5mm clearance (Loose fit) (d) 2.0 mm clearance (Extra loose fit)

Figure 5-4: Stiffness changes pre- and post-slip in conventional bolted joints with varying bolt-hole clearances.

The effect of bolt-hole clearance is not only evident at the ultimate failure point, but also in the entire load-displacement response. First, the extent of slip displacement increases with increasing bolt-substrate clearance. Second, the bolt comes into contact with the substrates after the slip and re-engages to carry the loads. The second stiffness after the slip event is also different for every bolt-hole clearance, and is indicated by slope 2 in Figure 5- 4.

As the bolt-clearance increases, the bolt-tilts and experiences a combination of bending and shear (see Figure 5- 5). The higher the dominance of bending, the larger the reduction in the slope of the load-displacement curve. Also, an increase in bolt-hole clearance means smaller contact surface for bearing, thereby higher stress leading to early failures.

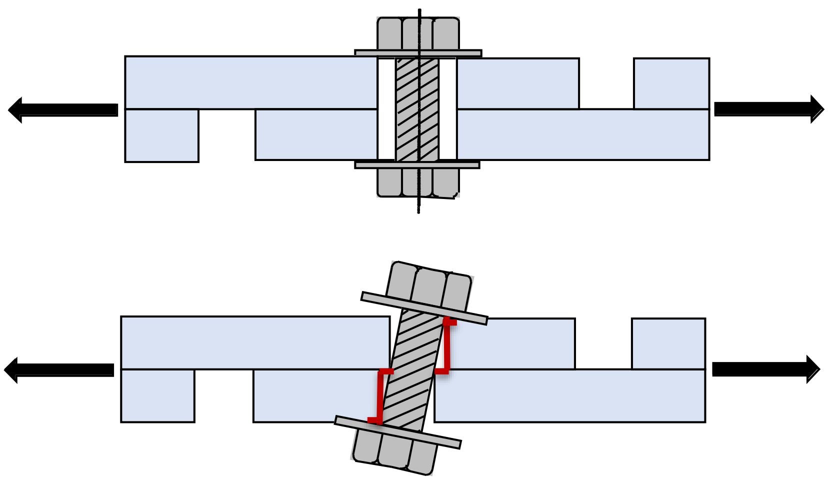


Figure 5-5: Schematic of pre- and post-slip deformation in conventional bolted joints.

As observed in Figure 5-4, a reduction in slope (stiffness) due to increasing bolt-hole clearance is clearly visible. The joint stiffness (marked as slope 2) was calculated to be 8.0 kN/mm, 8.0 kN/mm, 7.2 kN/mm and 7.0 kN/mm for close, normal-, loose-, and extra loose- fit clearances. Table 4-2 show the change in joint stiffness (after the slip, slope 2) as the clearance is varied from close fit (0.5mm) to extra loose fit (2.0mm). Additionally, the decrease in slope of all joints relative to the close-fit has also been highlighted.

Table 5-2: Reduction in joint stiffness of conventional bolted joint as a function of bolt-hole clearance.

Clearance	*Close*	*Normal*	*Loose*	*Extra loose*
Stiffness (kN/mm)	*8*	*8*	*7.2*	*7*
Percentage change from close to extra loose fit clearance	*-*	*0%*	*-10%*	*-12.5%*

5.2. Effect of Aluminum-filled Epoxy Insert on Hybrid Joints with Varying Bolt-Hole Clearances

Figure 5-6 shows the representative load-displacement responses of hybrid joints with aluminum-filled epoxy insert for each of the bolt-hole clearances. The initial segment in the load-displacement curve was linearly elastic up to ~ 10kN. This is the region wherein the compressive forces (clamping loads) are governing the behavior of the joint. Hence this region is the same for all joints irrespective of the insert. As explained in section 3.3 and section 4.3, hybrid joints do not exhibit bolt-adherend slip. However, a change in stiffness was visible around the slip load (~10 kN), indicating transfer of stresses from the substrate-to-insert-to-bolt and *vice versa*. Hence, around the slip-load the compressive forces are overcome by the applied shear forces and force transfer occurs through the insert to the substrate as indicated by the change in slope. Further application of load exhibited a non-linear response until the onset of delamination was reached. Once delamination starts, a progressive failure starts, and is characterized by a large increase in displacement with minimal increase in load until peak load is reached. Beyond the peak loads, the displacements increase while the load carrying capacity reduces until failure.

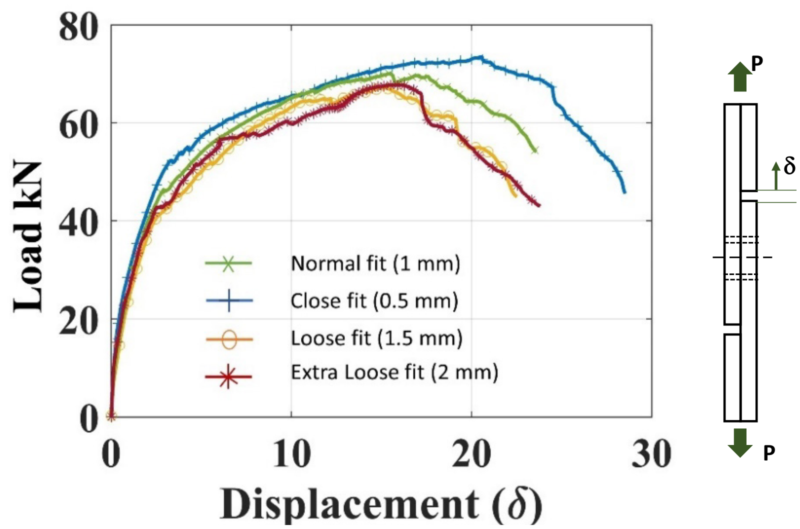


Figure 5-6: Load-displacement response of hybrid joints with aluminum-filled epoxy insert and varying bolt-hole clearances.

Figure 5-7 shows the effect of clearances on P_1 (onset of delamination), P_2 (load based on maximum slip displacement) and P_3 (Peak load) as a function of slip load in conventional joints for the hybrid joints with 'aluminum-filled epoxy inserts.' It was observed that the best performance in all parameters was obtained from loose (1.5 mm) clearance and the worst performance of all parameters was in the close-fit clearance. Overall, on average (P_1, P_2 and P_3 combined) the hybrid joints with the Aluminum filled epoxy inserts were ~3-8 times better than the slip load of equivalent clearance conventional bolted joints.

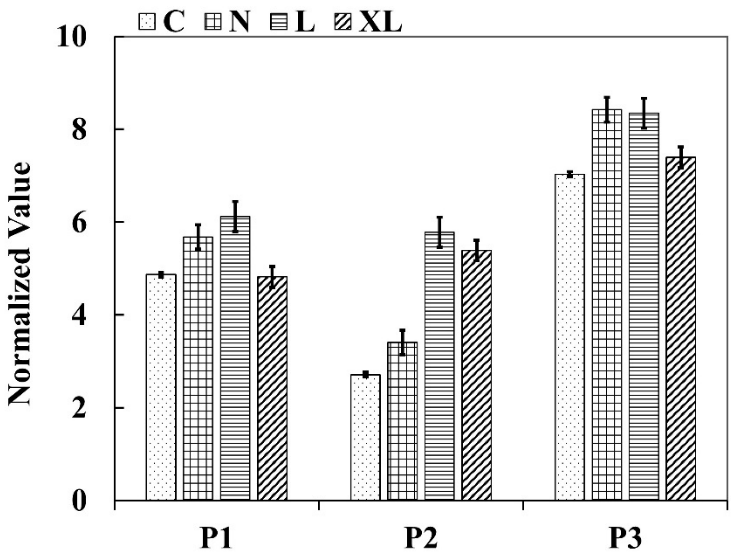
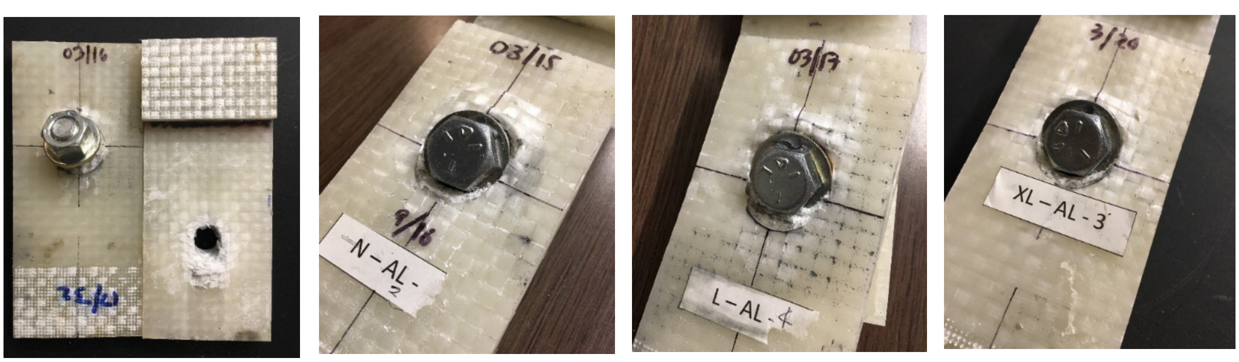


Figure 5-7: Effect of clearance on hybrid joints with aluminum- epoxy inserts.



(a) *(b)* *(c)* *(d)*

Close fit (0.5mm) *Normal fit (1mm),* *Loose fit (1.5mm)* *Extra loose fit (2 mm)*

Figure 5-8: Post failure images of with aluminum epoxy inserts at various clearances.

Figure 5-8 shows the post-failure images of hybrid joints with aluminum-filled epoxy as a structural insert in the bolt-hole clearances. Similar to that of conventional joints, the mode of failure changes with respect to bolt-hole clearance. If the clearance is small, the failure happens by bolt shear. When the clearance increases, the joints failed by pull through.

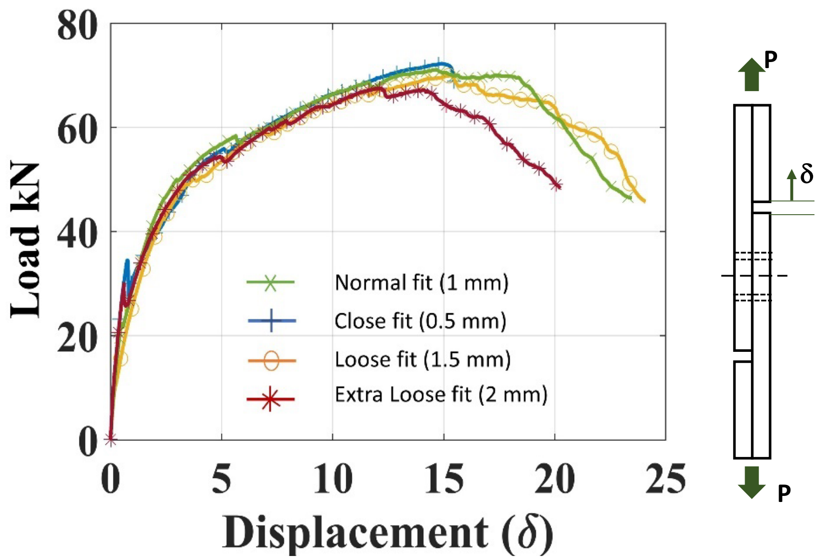


Figure 5-9: Load-displacement response of hybrid joints with Proset epoxy insert and varying bolt-hole clearances.

5.3. Effect of Proset Epoxy Insert on Hybrid Joints of Varying Bolt-Hole Clearances

Figure 5-9 shows the representative load-displacement responses of hybrid joints with Proset epoxy insert for each of the bolt-hole clearances. Similar to hybrid joints with aluminum-filled epoxy inserts (section 5.2), the initial segment in the load-displacement curve was linear elastic up to ~ 10kN. This is the region wherein the compressive forces (clamping loads) are governing the behavior of the joint. Hence this region is the same for all joints irrespective of the insert. The elimination of slip and the transfer of loads explained in the previous section for the 'aluminum-filled epoxy inserts' joint is also valid for this joint, and for brevity purposes not repeated here. One observation that was unique to the Proset epoxy insert joints was a significant drop in loads at ~30 kN. This was observed for Proset joints with all clearances. This drop is attributed to the brittle failure of the Proset epoxy insert. Further increase in applied load revealed onset and progressive delamination of the substrate until a peak load was reached, followed by failure similar to other joints in this work.

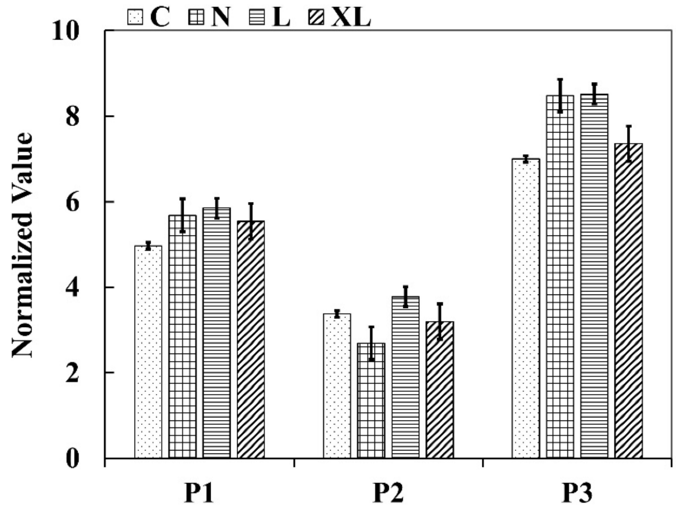
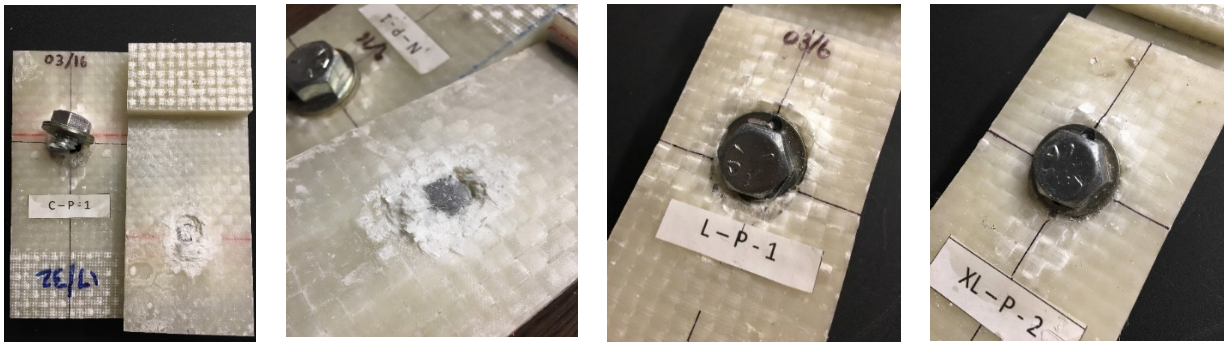


Figure 5-10: Effect of bolt-hole clearance on hybrid joints with Proset epoxy inserts

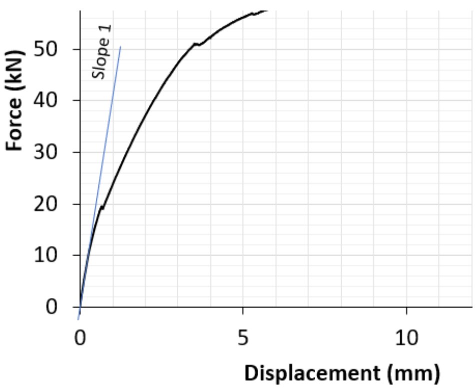
Figure 5- 10 shows the effect of clearances on P_1 (onset of delamination), P_2 (load based on maximum slip displacement) and P_3 (Peak load) as a function of slip load in conventional joints for the hybrid joints with 'Proset epoxy inserts'. Similar to that of aluminum filled epoxy inserts (section 5.2), it was observed that the best performance in all parameters was obtained from loose (1.5 mm) clearance and the worst performance of all parameters was in the close-fit clearance. Overall, on average (P_1, P_2 and P_3 combined) the hybrid joints with Proset epoxy insert were ~3-8 times better than the slip load of equivalent clearance conventional bolted joints.

Figure 5-11 shows the post failure images of hybrid joints with Proset epoxy as structural insert in the bolt-hole clearances. Similar to that of conventional joints, the mode of failure changes with respect to bolt-hole clearance. For close-fit clearance, bolt-shear failure occurs, and for all other clearances the joints fail with excessive delamination and bolt pull-through.

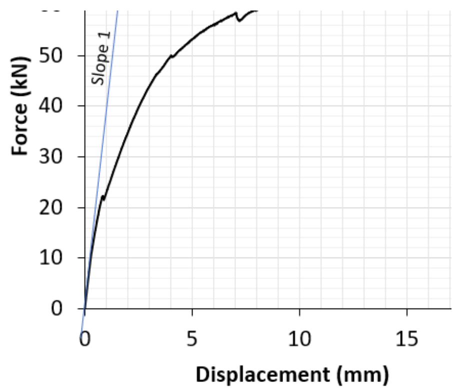


(a) *Close fit (0.5mm)* — *(b)* *Normal fit (1mm),* — *(c)* *Loose fit (1.5mm)* — *(d)* *Extra loose fit (2 mm)*

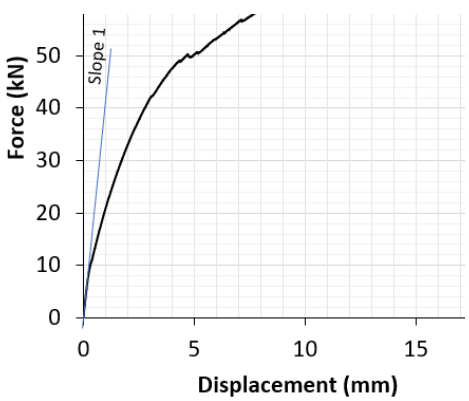
Figure 5-11: Post failure images of with Proset epoxy inserts at various clearances.



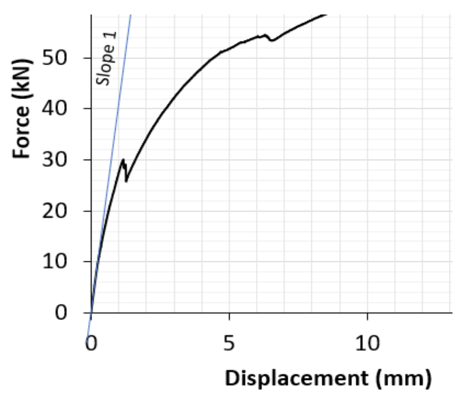
(a) 0.5 mm clearance (Close fit)



(b) 1.0 mm clearance (Normal fit)



(c) 1.5 mm clearance (Loose fit)



(d) 2.0 mm clearance (Extra loose fit)

Figure 5-12: Variation in Initial stiffness of hybrid joints with PRO-SET epoxy as a function of bolt-hole clearance

In terms of joint stiffness, joints with close fit clearance had higher stiffness relative to other joints in this case study. This is expected as the load gets transferred from the bolt to the substrate instantaneously. As the bolt clearance increases, the effect of the insert material on stress transfer increases. The insert material (matrix/adhesive) is an order of magnitude less stiff than the GFRP substrate and thereby supporting the reduction in stiffness observed in this study. Hence, from Figure 5- 12, it can be concluded that the joint stiffness decreases as clearance increases. Similar to other joints, once the delamination starts, the stiffness of the joint reduces gradually until it reaches its maximum load followed by failure. The decrease in joint stiffness as the bolt-clearance increases is quantified in table 5-3. It was observed that the joint stiffness reduced by ~33% in extra loose fit clearance joints relative to close-fit clearance joints.

Table 5-3: Reduction in joint stiffness as a function of bolt-hole clearance.

	Close	*Normal*	*Loose*	*Extra loose*
Stiffness (kN/mm)	*13*	*10*	*10*	*8.7*
Percentage change from close to extra loose fit clearance	*-*	*-23%*	*-23%*	*-33%*

5.4. Effect of Polyurethane Insert on Hybrid Joints of Varying Bolt-Hole Clearances

Figure 5-13 shows the representative load-displacement responses of hybrid joints with polyurethane insert for each of the bolt-hole clearances. Similar to hybrid joints with proset epoxy (Section 5.3) and aluminum-filled epoxy inserts (section 5.2), the initial segment of the load-displacement curve was linearly elastic up to ~ 10kN. This is the region wherein the compressive forces (clamping loads) are governing the behavior of the joint. Hence this region is the same for all joints irrespective of the insert. The elimination of slip and the transfer of loads explained in the previous section for ‘epoxy inserts’ joints is also valid for this joint and for brevity purposes not repeated here. One observation that was unique to the polyurethane insert joints was the rapid change in slope/stiffness after the ~10 kN mark. As explained earlier, this is the load corresponding to bolt-adherend slip wherein the compressive forces from clamping loads are overtaken by the applied shear forces. Hence, the transfer forces through the ductile polyurethane leads to this change in slope. Both the epoxy inserts (Aluminum-filled and Proset) are stiff and do not exhibit this slope change observed in polyurethane insert joints. Similar to all other joints, further increase in applied load resulted in the onset and progressive delamination of the substrate until peak load was reached followed by failure similar to other joints in this work.

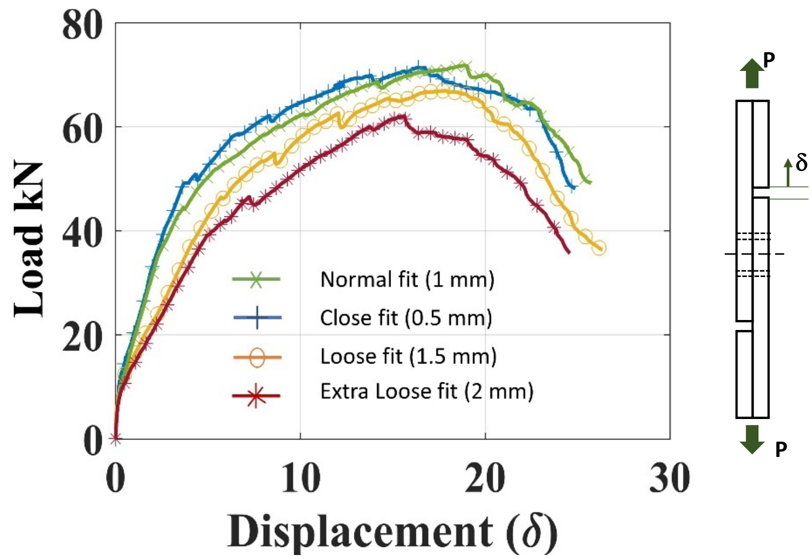


Figure 5-13: Load-displacement response of hybrid joints with polyurethane epoxy insert and varying bolt-hole clearances.

Figure 5- 14 shows the effect of clearances on P_1 (Onset delamination), P_2 (Load based on max. slip distance) and P_3 (Peak load) as a function of slip load in conventional joints for the hybrid joints with 'Polyurethane inserts.' Unlike epoxy inserts (section 5.2 & 5.3), the best performance in all parameters was obtained from joints with normal-fit (1mm) and loose-fit (1.5 mm) clearances and the least performance was observed in joints with extra loose-fit clearance. Overall, on average (P_1, P_2 and P_3 combined) the hybrid joints with Polyurethane insert were ~5 times better than the slip load of equivalent clearance conventional bolted joint.

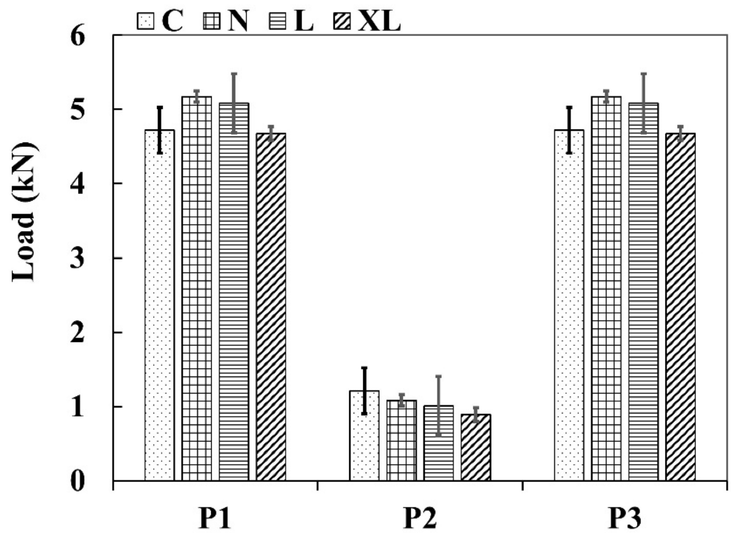
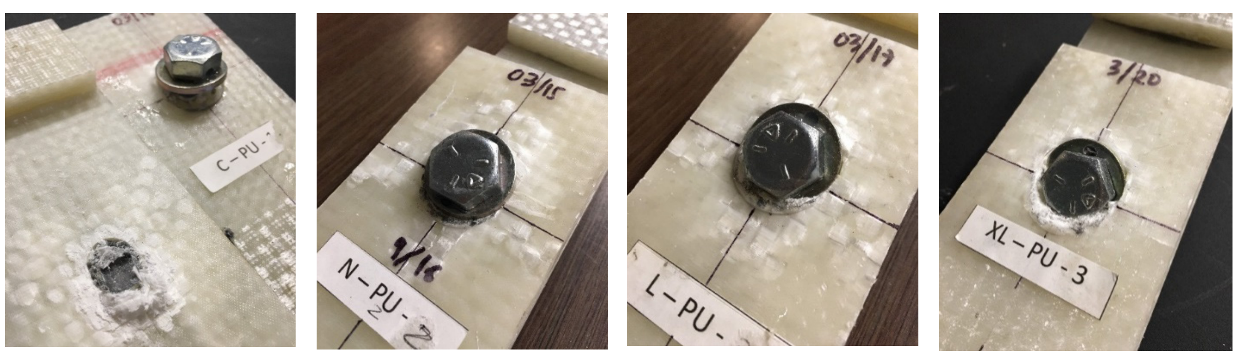


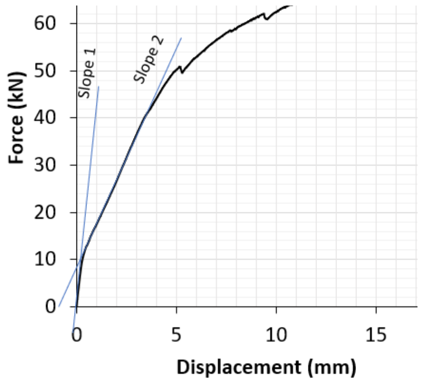
Figure 5-14: Effect of clearance on hybrid joints with poly-urethane epoxy inserts.

Figure 5-15 shows the post failure images of hybrid joints with Polyurethane as the structural insert in the bolt-hole clearances. Similar to that of conventional joints, the mode of failure changes with respect to bolt-hole clearance. For close-fit clearance, the bolt shear failure occurs, and for all other clearances the joints fail with excessive delamination and bolt pull-through.

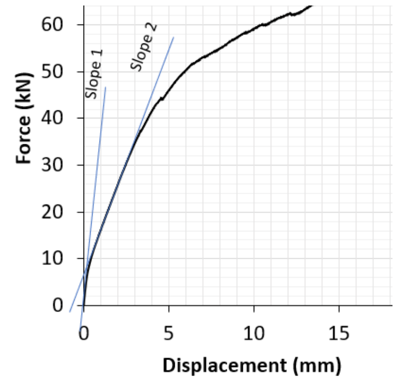


(a) *Close fit (0.5mm)* *(b)* *Normal fit (1mm),* *(c)* *Loose fit (1.5mm)* *(d)* *Extra loose fit (2 mm)*

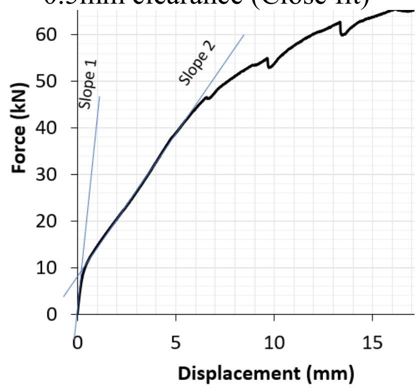
Figure 5-15: Post failure images of with Polyurethane epoxy inserts at various clearances.



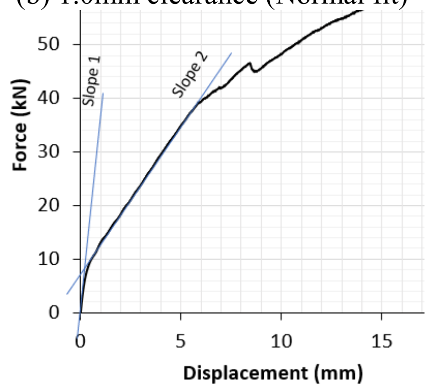
0.5mm clearance (Close fit)



(b) 1.0mm clearance (Normal fit)



(c) 1.5mm clearance (Loose fit)



(d) 2.0mm clearance (Extra loose fit)

Figure 5-16: Variation in Initial stiffness of hybrid joints with Polyurethane insert as a function of bolt-hole clearance

The change in stiffness after the 10 kN load (slip load) was calculated similar to that in the conventional joint (section 5.2) and the Proset epoxy insert (section 5.4). It can be observed from Figure 5-16 and Table 5-4 that the joint stiffness decreased with increase in the bolt-substrate clearance values. It was observed that the joint stiffness reduced by ~48% in extra loose fit clearance joints relative to close-fit clearance joints.

Table 5-4: Reduction in joint stiffness as a function of bolt-hole clearance.

	Close	*Normal*	*Loose*	*Extra loose*
Stiffness (kN/mm)	*10*	*9.7*	*6.2*	*6.2*
Percentage change from close to extra loose fit clearance	-	*-3%*	*-38%*	*-48%*

5.5. Chapter Conclusion

In this chapter, the effect of bolt-hole clearance on hybrid joints was studied for four different bolt-hole clearances for each of the three insert materials. Bolt-adherend slip was eliminated in all hybrid joints. Depending on the insert material, the performance of the hybrid joints could be tailored. All the joints having close-fit clearances experienced bolt shear failure. Similarly, all the joints with extra loose fit performed lower than normal and loose-fit joints. In other words, normal-fit and loose-fit joints had the best performance in both peak loads and onset of delamination relative to the slip load of equivalent conventional joints. Polyurethane insert joints had lower stiffness but higher ductility. Hybrid joints with epoxy inserts (aluminum filled and Proset) had a good balance of stiffness and toughness. Overall, the hybrid joints were 4 to 8 times better relative to their equivalent conventional joints. Finally, depending on the application, the insert material can be selected to tailor the joint behavior to meet application requirements.

Chapter 6: Summary, Conclusion and Future Directions

6.1. Summary

In this work, experimental characterizations of hybrid fastening systems comprised of glass fiber reinforced polymer (GFRP) composite substrates fastened using a fully threaded grade 5 steel bolts in ½” (12.5 mm.) diameter with varying (four) bolt hole clearance and three structural insert materials were performed. The GFRP substrates were manufactured using the vacuum-assisted resin transfer molding (VARTM) process. The preload was maintained at 75% of the bolt yield strength for all joints.

The objective of this work was to characterize/quantify the effect of: a) the adhesive insert and b) the bolt-hole clearances on the efficiency of the hybrid fastening system. For the first parameter, namely the effect of the adhesive insert, three adhesive insert materials were used. The adhesive insert materials used were PRO-SET epoxy resin, DEVCON epoxy filled with aluminum particles, and Polyurethane. All resulting joints were cured at room temperature for 48h prior to testing. For the second parameter, namely the effect of bolt clearance, four different bolt-hole clearances: close fit (0.5mm), normal fit (1.0 mm.), loose fit (1.5 mm.), and extra loose fit (2.0 mm.) were studied for each of the insert materials along with the control/conventional joint without any structural insert. All joints were tested in tensile lap-shear configuration at a loading rate of 5 mm / min. A total of 64 joints were experimentally tested.

The performance of the hybrid fastening system was compared to conventional joints with similar clearances. All conventional joints (without insert) experienced bolt-adherend slip which was characterized by sudden increase in displacement without any increase in load. The load corresponding to this phenomenon of bolt-adherend slip was termed the ‘Slip Load.’ In applications wherein small displacements are important, this bolt-adherend slip can be considered as the failure of the resulting joint. Hence, the performance of hybrid joints was compared with the slip load of conventional joint with equivalent clearance. Three parameters were defined to compare the performances of the hybrid joints with respect to the slip load. Parameter-1 (P_1) compared the 'load corresponding to onset of delamination (ODL)' with slip load of conventional joints of equivalent clearance. Parameter-2 (P_2) compared the 'load in hybrid joints corresponding to the maximum slip displacement in equivalent conventional joints' with slip load of conventional joint of equivalent clearance. Parameter-3 (P_3) compared the 'peak load in hybrid joints' to the slip load in conventional joints of equivalent clearance. In addition, the type and extent of damage of hybrid joints was compared with equivalent conventional bolted joints.

6.2. Key Conclusions

- Conventional bolted joints experienced 'bolt-adherend' slip wherein the compressive forces and associated friction forces due to clamping loads were overcome by the applied shear forces. In the slip event, the load does not significantly increase, but the displacement increases until the bolt tilts and is resting/bearing on the substrates.
- Hybrid bolted joints of all insert materials do NOT exhibit 'bolt-adherend' slip.
- The initial slope for all joints (hybrid and conventional) was similar. Additionally, the average slip load for all conventional joints (irrespective of clearance) was also similar. This is the region which is controlled by the clamping load on the bolt wherein the compressive forces and associated friction forces are larger than the applied shear loads. Since the torque applied was the same for all joints, the slip-loads and the initial slope of the load-displacement response was same for all joints irrespective of insert material or bolt-hole clearance.

- In conventional bolted joints, as expected, the maximum slip displacement increased with increase in bolt clearance. As the bolt clearance increases, there is more space available for the bolt to tilt/rotate and hence larger slip displacements.
- In conventional bolted joints, after the bolt-adherend slip, the increase in applied loads leads to onset of delamination at the locations of contact of the bolt with substrates.
- This delamination continues until the peak load is reached followed by progressive delamination until failure.
- In conventional joints, the stiffness of the joint after the slip event remains the same irrespective of the bolt clearance.
- For hybrid joints, once the applied load was larger than the equivalent slip load, the effect of insert material and the bolt-hole clearance was evident.
- For joints with polyurethane (ductile, low-stiffness) insert, a reduction in stiffness was observed in the loading region equivalent to the slip load in conventional joint. This shows that the insert material is activated after the slip load and acts as a structural element to transfer the load from the substrate to the bolt and vice-versa. Such reduction in stiffness was not observed for joints with both Proset and Aluminum filled epoxies. In short, Polyurethane insert joints had lower stiffness but higher ductility.
- Hybrid joints with epoxy inserts (aluminum filled and Proset) had a good balance of stiffness and toughness.
- All the joints having close-fit clearances experienced bolt shear failure.
- Similarly, all the joints with extra loose fit performed lower than normal and loose-fit joints.
- The failure mechanism of all conventional bolted joints exhibited severe delamination culminating with a bolt pull-through failure.

- The failure mechanisms of all hybrid joints were less severe than equivalent conventional joints.
- Overall, on average (P_1, P_2 and P_3 combined) the hybrid joints were ~5-8 times better than the slip load of equivalent clearance conventional bolted joint.
- Finally, depending on the application, the insert material can be selected to tailor the joint behavior to meet application requirements.
- Overall, this work is novel, and the first to report on the effect on clearance and varying adhesive insert materials for hybrid fastening joint.

6.3. Future Work

This work was the first to report on the effect on clearance and varying adhesive insert materials for hybrid fastening joint. While the merits of hybrid fastening were clear, there is a need to quantify the stress-concentrations and its reductions due to the addition of these structural inserts. Novel measurement techniques such as embedded fiber-optic sensors can be used to provide accurate stress measurements at the appropriate locations of the hybrid joint. Such precise stress measurements will also allow for the selection of the right type of insert material based on the applications. Secondly, it is impractical and infeasible to perform experimental characterization for all the design parameters of hybrid fastened joints. Instead this work can be used to develop and validate numerical simulations. The experimentally validated simulations can then be used to explore the design space without the costly trial-and-error approach. Lastly, this work tested three samples per case. For industrial applications, a more detailed statistical testing needs to be performed prior to field applications. Overall, the hybrid fastened joints are tailorable based on the application needs and hence have a great potential in a wide range of applications.

APPENDIX

APPENDIX: List of Publications by the Candidate at the Time of Dissertation Submission

[1]. Balachandran, S. Ramli, N. Abdol, P. Soroushian, Transformation of Landfilled Ash into a Hydraulic Binder with Concurrent Capture of Carbon Dioxide for Effective Hazardous Waste Immobilization, September 2018

[2]. K. Zhu, S. Ramli, A.G.N.D. Darsanasiri, A. Balachandran, Production and Characterization of a Hydraulic Cement with Landfilled Coal Ashes of Different Disposal Durations, Using Carbon Dioxide as a Raw Material, September 2018

[3]. A.G.N.D. Darsanasiri, F. Matalkah, S. Ramli, P. Soroushian, Ternary Alkali Aluminosilicate Cement Based on Rice Husk Ash, Slag and Coal Fly Ash, April 2018

[4]. K. Zhu, F. Matalkah, S. Ramli, A. Balachandran, Carbon Dioxide Use in Beneficiation of Landfilled Coal Ash for Hazardous Waste Immobilization, March 2018

[5]. X. Wang, F. Matalkah, N. Abdol, S. Ramli, P. Soroushian, A. Balachandran, Effects of the duration of landfill disposal on the physicochemical, minerology and toxicity characteristics of coal ash. March 2018

[6]. X. Wang, K. Zhu, S. Ramli, P. Soroushian, A. Balachandran, Conversion of Landfilled Ash into Hydraulic Cements under Different Environments, November 2017

[7]. S. Ramli, K. Zhu, F. Matalkah, P. Soroushian, A. Balachandran, Development of Refined Chemistries and Processing Methods for Integration of Carbon Dioxide into a Hydraulic Binder for Effective Heavy Metal Immobilization, August 2017

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[12]. Cloud, G.L., Hybrid Fastener, U.S. Patent 10,400,813 B2. Issued 3 September 2019. Assigned to Michigan State University

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