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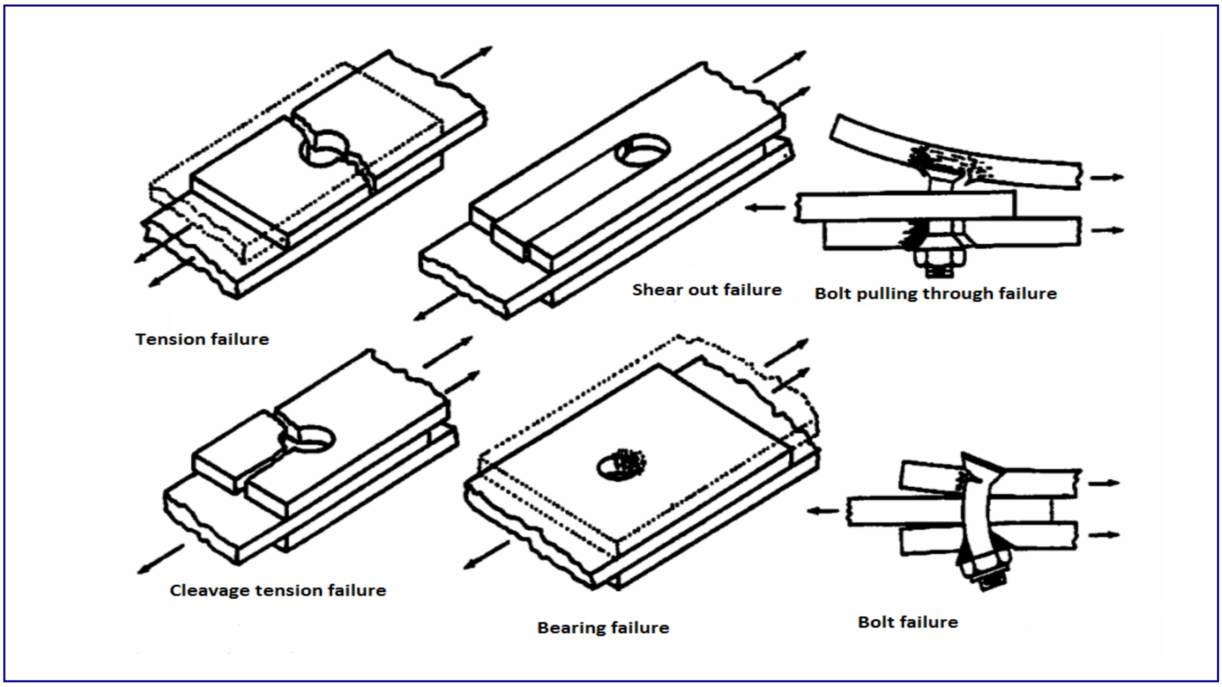

CONNECTIONS IN STRUCTURAL FRP MEMBERS

Master of Science Thesis in the Master's Programme Infrastructure and Environmental Engineering

MOHAMMAD SADEGH KHANI

Department of Civil and Environmental Engineering
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Common failure in FRP bolted connection ,Figure source: Mosallam, A. S, & Knovel (e-book collection). (2011). ''Design guide for FRP composite connections''. Reston, Va: American Society of Civil Engineers.

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ABSTRACT

At the present, there is an increasing demand for alternatives to conventional construction materials in infrastructural applications. In this regards, application of new construction materials such as FRPs has attracted a freat deal of attention. One of the obstacles towards widespread use of FRP materials in infrastructural applications is connection of FRP members. Due to orthotropic nature of FRP materials and their failure susceptibility with regard to stresses perpendicular to the plane of the FRP member, the design of connections in such members is a rather complicated task and some behavioral aspects of these connections are still not known. In order to use the FRP material in structural applications a better understanding of FRP connections and setting proper design methods is very important.

This thesis is a part of an on-going project in the field of FRP composite connections at Chalmers University of technology.

The thesis provides short review on different types of connection use to join FRP structural members such as mechanical, bonded and hybrid connections with focus on mechanical connections. Different aspects such load transfer mechanism and different failure modes have been presented. Design parameters affecting the strength of the joint are introduced and discussed.

The results of an experimental testing program which was conducted in the framework of the research project is presented. In the first stage, experiments were conducted in order to determine the material properties and in the next stage, double lap shear joints were performed under quasi static loading to determine the characteristics of bolted and bonded joints.

Due to importance of the fatigue, especially in the infrastructural applications, this phenomenon has been investigated in the thesis.

Key words: GFRP, CFRP, FRP bolted Connection, adhesive Connection,Hybrid connection.

Contents

Preface

First of all, I would like to express my gratitude and cordial thanks to my examiner Professor, Reza Haghani for his worth-while and constructive key-guidance to successfully complete this project. I am indeed happy to see his distinguished comments and notation that has helped me to upgrade the level and quality of this project.

I would like to give special thanks to Valbona Mara for her support, time and shared-thought. I also like to give a warm thanks to Sebastian Almfeldt for his support for our experimental tests.

Finally, I am really grateful to my wife for her inspiration and patience to see my project completed.

Mohammad Sadegh Khani

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Notations

E_a	Modulus of elasticity of adherent
E_C	Adhesive film tensile modulus in peel
W	Width of the joint
W_X	Spacing between the fastener hole in the x-direction
W_y	Spacing between the fastener hole in the y-direction
T_S	Applied axial force, (N)
N_{sd}	Pulling through failure force
P_0	Initial load, (kN)
M_e	Bending moment in the adherents at the end of the overlap
B	Relaxation exponent constant
P_K	Characteristic load per unit width

Roman lower case letters

c	Half the bonded overlap length in the direction of applied load
e	Edge distance (distance from hole centre to short edge)
s	Side distance (distance from the hole centre to the long edge)
t	Thickness of laminate considered
d_b	Fastener Shank diameter
r	Radius of bolt bet area, (mm)
α	Angle of inclination of bolt threads
θ	Angle of static friction
σ	Average baring stress
P	Applied load
D	Bending stiffness of the adherents
n	Number of bolts
$d\ or d_b$	Bolt diameter or fastnar shank diameter
k_{te}	Elastic stress factor, in the net tension failure mode
C	Stress concentration coefficient
τ	Shear stress
α	Angle of inclination of bolt threads
$f_{V,Rd}$	Pulling through strength
d_r	Washer diameter
d_h	Hole diameter
$\sigma_{c_{max}}$	Peak adhesive peel stress

τ_p	Peak adhesive shear stress
t_0	Adherent thickness
t_a	Adhesive thickness
ϑ	Poisson ratio of adherent
$\tau_{0\ allowable}$	Allowable adhesive shear stress
$\sigma_{0\ max}$	Allowable adhesive peel (tensile) stress
$\sigma_{0\ allowable}$	Allowable adhesive peel (tensile) stress
$\sigma_{z\ allowable}$	Allowable adherent through-the-thickness tensile stress

1 Introduction

Historically, four traditional construction materials including steel, concrete, timber and masonry have dominated the construction industry. Masonry and timber were the main materials for building structures and also infrastructures up until a few hundred years ago. (Friberg and Olsson(2014).Today, timber, steel and concrete are the most common used materials in the construction. However, these materials suffer from a number of drawbacks such as susceptibility to corrosion, degradation and other aging problems. There is therefore an increasing demand at the present for alternatives to the conventional construction materials. In this regard, fiber reinforced polymer (FRP) composite materials have emerged as a new construction material in the past 30 years due to their superior mechanical, chemical and physical properties.

The FRP composites were first developed during 1940s for military and aerospace applications, where their high strength and light weight used to optimum benefit. The Fiber reinforced polymer composites have high strength-to-weight ratios with outstanding durability qualities in a variety of environments and are easy and quick to install. Setting the mechanical properties of polymer composites by appropriate choice and direction of fibers is a distinct advantage of using FRP materials. The FRPs are resistant to corrosion and they are dimensionally stable (Friberg and Olsson(2014). These materials are desirable in many applications such as repairing of existing structures and construction of new ones (Tang & Podolny, 1998; Muniz & Bansal, 2009).

Figure 1 FRP bridge and strengthening and repair of bridges. ***.*** *Figure sources: GEF Company,Tenroc Company.*

At the present, FRP materials are used for construction of whole and hybrid FRP bridges for both vehicular and pedestrian purposes.

At the present, the connection of FRP members is an obstacle in front of FRP bridge industry. FRP bridges cannot be manufacture off site, and there is demand to produce them in segments and connect them on-site. Then there is demand for some reliable methods to connect the segments to each other such as mechanical connections, bonding, etc.

1.1 Background

The FRP was first used in building industry during the 1970s as non-load bearing infill panels manufactured by hand lay-up process; using the polyester polymer. Afterwards using the FRP as a material for structure was increasing steady and at the present FRP is known as a construction material.

The investigations on characterization of FRP connections (especially mechanical connections) started in aerospace industry in the US in the mid 1960thas there was a demand at that time to achieve a proper design for connections. The conventional plastic design method which had been used in bolted connection in steel and aluminum and other ductile materials is not applicable to FRP connections with the brittle behavior. Moreover, using linear elastic analysis is not appropriate due to great strength increase resulted from fine micro failure in the intermediate vicinity of small bolts holes (Hart-Smith 1989).Nowadays based on research work which has been conducted, different recommendations and standards are prepared for FRPs including the design criteria for FRP connections.

1.2 Aim, objectives and methodology

The present knowledge about the FRP connections is pretty advanced knowledge. However, this sophisticated knowledge is not good enough among structural Engineers.

There are a number of differences which distinguishes the connections in structural applications from those in other engineering areas such as, the thickness of the adherents, mechanical properties of adherents, the size of the fasteners, the type and thickness of the adhesive layer in bonded joints, etc. which influence the design assumptions and make many design theories in other fields (e.g. aerospace) not working in this field. Therefore it is important to study the behaviour of such FRP joints and get a good understanding about the behaviour of connections and joints.

At the present, there is no unified approach for design of the FRP connections, hence designing the connections and predicting their real behavior involves a great deal of uncertainty. The aim of this project is to provide a better understanding of the behavior of FRP connections.

In order to reach this aim two objectives were set as following.

- To carry out a literature review on FRP connections. Available codes, design recommendations and other available documents and materials have been studied to get a clear picture about the behavior and identify important design parameters in FRP connection.
- To perform experimental tests to study the behavior of bonded and mechanical joints including stiffness, failure loads and modes of failure. .

2 FRP structures

2.1 Characteristics of FRP materials

In this section a brief introduction of FRP materials and structures is presented. It is crystal clear that in connections both the connected and the connector's material properties play a significant role in the design; thereby, a short review of the FRP material can be useful.

FRPs are composite materials consisting a polymeric matrix reinforced with fibers. Like any other composite material every component (i.e. the fibers and the matrix) affects the final property of the FRP material. Moreover, size, shape, volume, orientation and distribution of fibers have influence on the final properties. The FRP material in essence is anisotropic and the fiber orientation and arrangement of them play an important role in the FRP properties. The figure below illustrates the FRP material both in micro and macro scale.

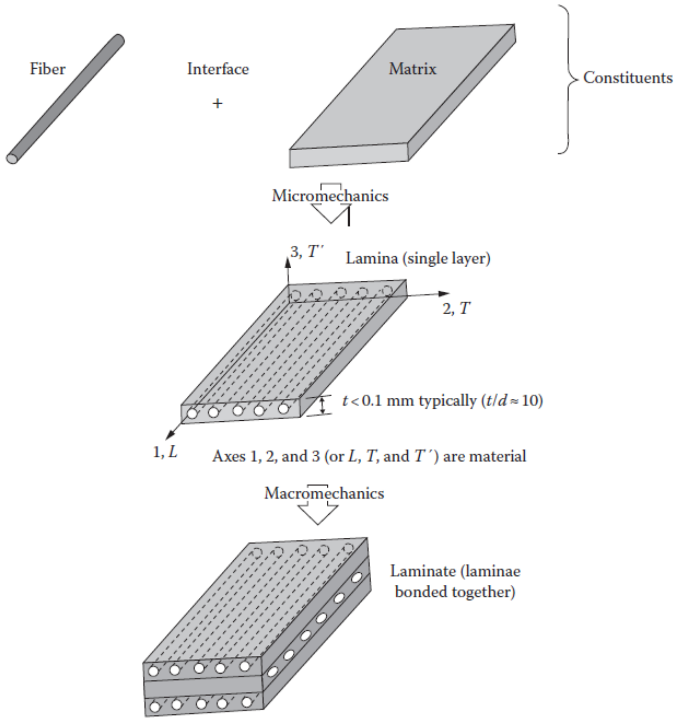


Figure 1 FRP material in micro and macro scale_ Source: The International Handbook of FRP Composites in Civil Engineering

2.1.1 Fiber

A fiber, which is a long filament, is made out of a single material such as ballast fiber, glass, aramid or carbon. The main purpose of the fiber is to provide sufficient strength and stiffness (Clarke 1996; Bisby 2006). Due to the nature of the fibers as long filaments, the fibers provide strength and stiffness mainly in the direction of the fibers (longitudinal direction). However, the fibers should provide a sufficient aspect ratio in more than one direction in order to provide a reinforcing function in the transversal direction as well (Halpin, Hastak & Hong 2004). The figure 2 shows the differences between fibers, matrix and FRP stress-strain characteristic. It is clear that the FRP as final material is completely dependent on the fiber characteristics.

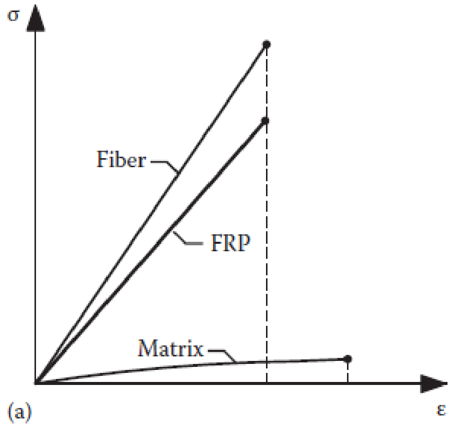


Figure 2 FRP component characteristic- Source: The International Handbook of FRP Composites in Civil Engineering

The fibers generally represent about 30-70% of the volume and 30% to 70% of the weight depending on the manufacturing technique and the form of the reinforcement in FRP (Potyrala, 2011;Clarke, 1996; ZRMK et al., 2013).

The three types of fibers that are the most common in civil engineering applications are: glass, aramid and, to a lesser extent, carbon fibers (Potyrala, 2011; Muniz & Bansal, 2009). They are suitable for different types of applications depending on requirements such as strength, stiffness, cost, durability and availability (Bisby, 2006).

The Glass fiber is the most common reinforcement in FRP composites, where it stands for approximately 90% of the market (Chlosta, 2012). Glass fibers are typically used in low-cost applications of polymer matrix composites. The Glass fibers are a processed form of glass, and consist of a number of oxides (largest extent of silica oxide) and raw materials (such as limestone, fluorspar, boric acid, clay etc.) (Potyrala, 2011). Due to that, glass fibers that containing silica they are in general very sensitive to alkaline environments (Friberg and Olson 2014). Some disadvantages of glass fibers are reported to be: low modulus of elasticity, poor abrasion resistance and poor adhesion to polymer matrix resin in presence of moisture. (Friberg and Olson 2014).

The most common glass fibers are E-glass fibers, which is the best choice of fiber type if the highest strength as well as electrical and thermal resistance is strived for (Clarke 1996). The “E” in E-glass stands for electrical since it was initially developed for electrical application (Kaw, 2005,Friberg and Olson, 2014).The other different types of glass fibers available for various applications are: “A” or “AR” glass for alkaline resistance , “C” for corrosion resistance , “S” and “R” for high strength and stiffness (Zoghi, 2013). The table 1 shows the typical properties of glass fibers.

Table 1 Typical properties of glass Fiber Source: The International Handbook of FRP Composites in Civil Engineering

Properties	*E-Glass*	*A-Glass*	*S-Glass*	*C-Glass*	*R-Glass*	*D-Glass*	*High Modulus*
Density,ρ(g/cm³)	*2.54*	*2.45*	*2.49*	*2.45*	*2.58*	*2.14*	*2.89*
Tensile strength,σ_{ult}(GPa)	*3.54*	*3.30*	*4.58*	*3.31*	*4.40*	*2.50*	*3.40*
Elastic modulus,E(GPa)	*72.4*	*69*	*85.5*	*69*	*84.8*	*55*	*110.4*
Diameter,d(μm)	*3-20*	-	*8-13*	-	-	-	-
Thermal expansion $\alpha_{L(10^{-6}/°C)}$	*5.0*	-	*2.9*	*6.3*	-	*3.1*	-
Max operation temp.(°C)	*550*	-	*650*	*600*	-	*477*	-

Carbon fiber is one of the two types of high-performance fibers used in civil engineering applications (Potyrala, 2011). The use of carbon fibers was increasing and between the years 1998 and 2010. The worldwide usage of carbon fibers was doubled to an amount of 30.000 tons annually (Chlosta, 2012). It has been used in many civil infrastructure applications, including seismic rehabilitation, retrofitting and repair of the structural system such as concrete beams and columns. The Carbon fibers are generally used when high strength and stiffness is required and where a lower weight justifies the higher cost (Cytec n.d, 2014). The Carbon fibers are furthermore considered to be the most durable fiber type (Friberg and Olson, 2014). Based on the fabrication method carbon fibers are categorized to three main groups as PAN, rayon and pitch. The table below shows the typical properties of Carbon fibers.

Table 2 Typical properties of carbon fibers. Table source: The International Handbook of FRP Composites in Civil Engineering

Properties	PAN(Type I)	PAN(Type II)	Pitch	Rayon
Density,ρ(g/cm³)	1.95	1.75	2.0	1.7
Tensile strength,σ_{ult}(GPa)	2.4-2.7	3.4-4.5	1.55	2.50
Long.Elastic modulus,E_1(GPa)	380	230	380	500
Transverse .elastic modulus,E_T (GPa)	12	20	-	-
Diameter,d(μm)	7-10	8-9	10-11	6.5

Long thermal expansion $\alpha_{L(10^{-6}/°C)}$	-0.5	-0.5	-1.0	-0.9
Transverse thermal expansion $\alpha_{L(10^{-6}/°C)}$	7-12	7-12	8	7.8

Aramid fibers are the second of the two types of high-performance fibers used in civil engineering (Potyrala 2011). The fiber is known as manmade and is used in many civil engineering applications. Aramid fibers are mostly named as organic fibers and Kelvar® (produced by Dupont) is the most commercially recognized brand (Zoghi, 2013). The organic fibers have high toughness and this characteristic make them useful in the impact and ballistic applications. The disadvantages of aramid fibers are known as low compressive strength, susceptibility to creep, moisture absorption, sensitivity to UV light, temperature-dependent mechanical properties and high cost.

Table 3 The typical properties of organic fibers. Table source: The International Handbook of FRP Composites in Civil Engineering

Properties	*K29*	*K49*	*K68*	*K119*	*K129*	*K149*
Density,ρ(g/cm³)	*1.44*	*1.44*	*1.44*	*1.44*	*1.45*	*1.47*
Tensile strength,σ_{ult}(GPa)	*2.9*	*3.0*	*2.8*	*3.0*	*3.4*	*2.4*
Long.Elastic modulus,E_1(GPa)	*70.5*	*112.4*	*101*	*55*	*100*	*147*
Diameter,d(μm)	*12*	*12*	*12*	*12*	*12*	*12*
Long,thermal expansion $\alpha_{L(10^{-6}/°C)}$	*-4.0*	*-4.9*	-	-	-	-

The graph in the figure 3 illustrates stress-strain curves of the different kinds of fibers. The tensile strength are also has compared with steel wires.

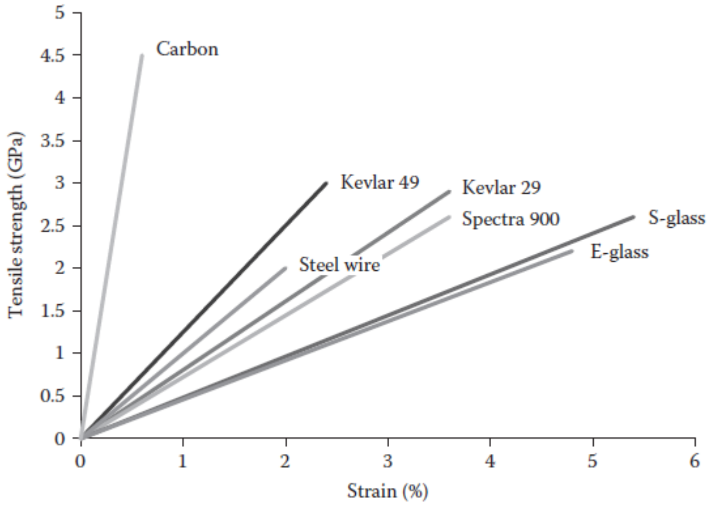


*Figure 3 Stress strain in different FRP material. Graph source: The International Handbook of FRP Composites in Civil Engineering***.**

As stated before, regardless of fiber kind and mechanical properties of fiber, the fiber arrangement is also important in FRP material properties. The fiber arrangement can be assigned into three main categories which are unidirectional, bidirectional and random (Clarke, 1996). The unidirectional is referred to the case when all fibers are arranged in one direction (Clarke, 1996).The bidirectional is formed when fibers are arranged in two directions either as 0° and 90° or ±45° (Clarke, 1996). This is performed with woven or non- woven fabrics (Clarke, 1996). For the arrangement termed random, which also is referred to as multidirectional fiber direction, the fibers are randomly distributed (Clarke, 1996). In general better mechanical performance is achieved of the composite if continuous fibers are used instead of chopped fibers (Clarke, 1996).

2.1.2 Polymer matrix

A matrix is composed of resins, fillers and additives (Potyrala, 2011) as well as catalysts and in some cases accelerator, release agents, inhibitors, monomer etc. (Clarke, 1996).

A matrix has different rules in composite materials like the following:

- Holds the fibers together and arranges them as intended
- Transfers the load between fibers through shear
- Separates the fibers within the composite material
- Gives stiffness and shape to the member
- Reduces or stops the crack propagation rate by letting the fibers to act independently
- Protects the fibers from environmental impacts such as chemical and mechanical
- Increases ductility and impact strength
- Shields from abrasion for notch sensitive fibers
- Provides shear, transverse tensile and compression properties

The governing parameters regarding the mechanical properties of the bond between fiber and polymer are both the compatibility between matrix and fiber, called the "interface", in addition with the loading direction and angle between fibers (Potyrala, 2011; Hollaway, 2010).

The characteristic of the bond between the fibers and the matrix is of important since it controls the load transfer in the structure (Bisby, 2006).

The polymer matrix is highly viscoelastic and the viscoelastic behavior of the FRP material mostly comes from the viscoelastic behavior of matrix. The matrix material is also temperature dependent. At increased temperature, at low loading rates or long-term loading, the response tends to be more ductile, while at low temperature and high loading are result in a rigid and more brittle behavior (Zoghi, 2013). The mechanical properties of the polymer material drop drastically when reaching the glass transition temperature (Zoghi, 2013). The glass transition temperature is the temperature, when the polymer softens, meaning that it changes from hard (often brittle) solid state to more rubber–like (soft and tough) solid state (Zoghi, 2013). Polyester, vinyl ester and epoxy are the most common matrices used in civil engineering applications. The table below shows some properties of resin according to (Zoghi, 2013) and (Malek, 1996).

Table 4 Typical properties of resin and matrices. Table source: The International Handbook of FRP Composites in Civil Engineering

Resin Type	*Tensile strength (MPa)*	*Modulus of Elasticity (GPa)*	*Density (kg/m^3)*	*Cure Shirinkage(%)*
Polyester	*35-104*	*2.1-3.5*	*1100-1400*	*5-12*
Vinyl ester	*73-81*	*3-3.5*	*1100-1300*	*5-10*
Epoxy	*55-130*	*2.8-4.1*	*1200-1300*	*1-5*

2.2 General properties of FRP

The FRP material properties are presenting in the table 5 and also in order to have a better understanding the material properties of conventional material is also stated. The table below compares typical properties of FRP, fiber, epoxy, concrete and steel.

Table 5 FRP and the material properties. Table source: The International Handbook of FRP Composites in Civil Engineering.

Properties	*FRP[a]*	*Fiber*	*Epoxy*	*Concrete*	*Steel*
Compressive Strength (MPa)	*125-2400*	*-*	*55-100*	*25-150*	*200-2000*
Tensile strength(MPa)	*400-3000*	*1800-5000*	*9-20*	*1-6*	*200-2000*

E-Moulus(GPa)	*35-500*	*60-800*	*0.5-20*	*25-50*	*200*
CTE$_{(10^{-6/°C})}$	*≈ 0(longitudinal)* *25-30(Transverse)*	*-6 to 5.0 (Longitudinal)* *~ 45^b (Transverse)*	*25-30*	*8-12*	*10*
Density,ρ(kg/m^3)	*1300-2200*	*1400-2600*	*1200-1300*	*2400*	*7800*
Poisson ratio	0.25-0.35	0.25-0.35	0.3	0.15-0.2	0.3

CTE, Coefficient of thermal expansion

[a] FRP based on glass, carbon or aramid fiber with epoxy matrix

[b] For aramid fiber (for carbon and glass, the transfer CTE is similar to the longitudinal (CTE)

Some important engineering properties both in compression and tension of the three different kinds of FRP material more separately are also stated in the tables 6.

Table 6 Poperties of different kinds of FRP. Table's source: The International Handbook of FRP Composites in Civil Engineering

FRP type	*Tensile strength (MPa)*	*Modulus of Elasticity (GPa)*	*Ultimate Strain, $\varepsilon fu_{(\%)}$*
CFRP	*600-3000*	*80-500*	*0.5-1.8*
GFRP	*400-1600*	*30-60*	*1.2-3.7*
AFRP	*600-2500*	*30-125*	*1.8-4.0*

FRP Type	*Compressive to tension Ratio $F_{f,comp}/f_{f,tens}$*	*Modulus of Elasticity ,E_f (GPa)*
CFRP	*0.78*	*0.85*
GFRP	*0.55*	*0.80*
AFRP	*0.2*	*1.00*

Like all materials, the environmental conditions affect the properties of FRP material. The most affective environmental parameters, which have been the subject of several researches, are: temperature, thermal stresses like freeze and thaw, moisture, acidic or alkane environment and ultraviolet radiation. The structures are usually subjected to a combination of these environmental conditions, in which two common forms are a combination of temperature and moisture. In the FRP composite material, fibers exhibit relatively high thermal stability, whereas polymers are strongly affected by the temperature (Zoghi, 2013). One of the influential parameters in FRP properties is moisture. Experimental that has been done on the effect of moisture reported that there was not any reduction in tensile strength in CFRP material whereas GFRP and AFRP. (Mosallam, A. S., & Knovel, 2011). The same reference has also reported that 30% and 35% tensile reduction in GFRP and AFRP in the wet-dry experimental test. The experimental was set such that can be able to model the condition for 50 years period (Mosallam, A. S., & Knovel, 2011).

In addition to the environmental effects, the effect of relaxation and creep and also cyclic loading condition (fatigue) are important in FRP materials. The Creep and relaxation are two parameters which are almost similar in essence. Table 7 shows the degradation level under fatigue (cyclic) loading condition. The table 7 shows the degradation of initial strength of different kinds of FRP materials per decade of logarithmic fatigue lifetime in tension-tension loading.

In the following chapters the fatigue will be discuss more in detail.

Table 7 Degradation of FRP under fatigue, Tension-tension. Table's source: The International Handbook of FRP Composites in Civil Engineering.

FRP type	*Degradation of initial static strength per decade of logarithmic fatigue lifetime*
CFRP	*≈ 5%*
GFRP	*≈ 10%*
AFRP	*≈ 5%-6%*

Table 8 also shows the fatigue in the two million cycles for different kinds of FRP and also prestressing steel.

*Table 8 Fatigue strength after two million cycles. Table's source: The International Handbook of FRP Composites in Civil Engineering***.**

Type of material	σ_{max}/f_{tk} [a]	$\Delta\sigma$ [b] *(MPa)*
Prestressing steel	*≈ 0.6*	*≈200*
E-glass/polyester (rod)	*≈ 0.5*	*≈60*
E-glass/epoxy (rod)	*≈ 0.5*	*≈ 75*
Aramid/vinylester (rod)	*≈ 0.6*	*≈235*
Carbon/vinylester (rod)	*≈ 0.6*	*>350*
Carbon/epoxy(strand)	*≈ 0.6*	*≈310*

[a] Applied maximum stress as a function of characteristic tensile strength of the reinforcement

[b] Stress range yielding fatigue failure at two million cycles

In the cycling load condition growth of internal or surface flaws may occur, resulting in a reduced mechanical strength compare to the short term static strength. (Zoghi, 2013) .

2.3 Applications

The FRP is widely used in industries such as aerospace, construction, offshore and marine, appliance and business equipment, corrosion resistance equipment, electronic, consumer products and transportation.

In the civil engineering industry, like in the other industries, there are on-going efforts to improve design and construction technologies to get better economic solutions for engineering problems. The FRP industry is a billion dollars industry worldwide. The FRP materials have potentials that fit them well for different industries. The FRP as a construction material offers advantages such as high specific strength, light weight, high performance speed, good durability, fitting well with structural retrofitting demands and also environmental resistance. The main characteristics of FRP materials that made them favorable in different technologies is the high strength to weight ratio and also high stiffness to weight ratio.

For the structural engineering applications Halloyway (Halloway2010) has explained and categorized FRP applications in civil Engineering using the flowchart shown in Figure 4.

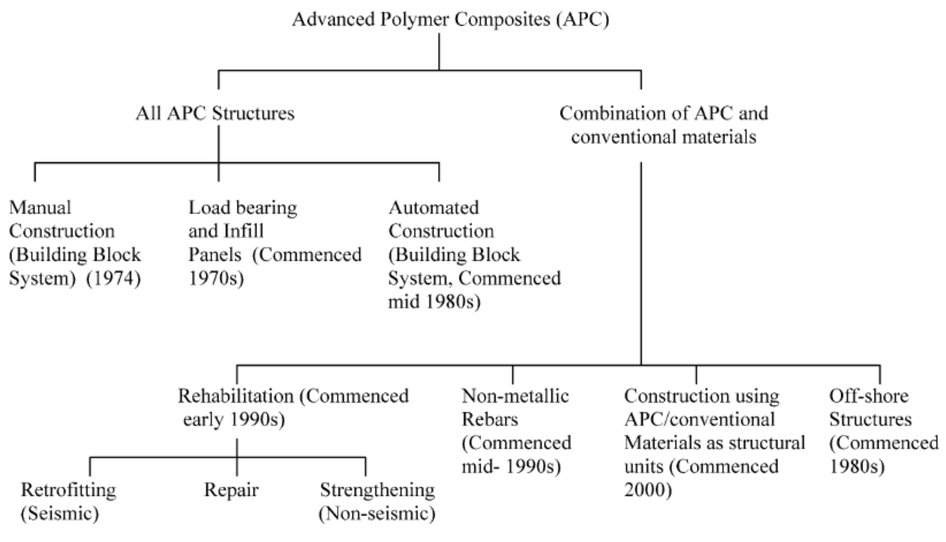


Figure 4 FRP applications in civil Engineering-Holloway 2012.

FRP materials can be used as the main construction material or can be used in combination of conventional materials. At the present, using FRPs as the main material it is expensive; however it can be economical for special purposes. For instance, it can be used in manufacturing bridge decks. The weight of the bridge deck is quite important in design especially in long span bridges. The maintenance cost and time of maintenance and performance can also be diminished by using the FRP materials. The fast assembly of FRP panels is one of the advantages of using FRP materials for this purpose. By using FRP panels both construction time and energy consumption will be decrease due to the weight of the material.

The FRP structures are lighter in comparison to the structure with the conventional material. The reason is attributed to the difference between the densities of FRP materials in comparison to that of conventional materials, whereas for instance the unit weight of FRP is about 15kN/m^3 in compare to 23.6 kN/m^3 for concrete.

Another example of using FRP materials as construction material is the road culverts. The FRP is corrosion resistant and can be a great choice in underground applications where there is a risk of corrosion due to harsh environment. The culverts which constructed by FRP material can be beneficial in conditions where both steel and concrete culverts are vulnerable. Using FRP cables in suspension bridges instead of steel cables is another application area where FRPs are used as main construction material. This application requires materials that incorporate high tensile strength, low weight and corrosion resistance. In this context, the FRP materials are fitting well with demands related to offshore structures and oil industry. FRP materials can also be used for strengthening and repair purposes. For instance, the FRP material are used for retrofitting concrete structural elements. Retrofitting of concrete columns to withstand earthquakes is a common and widespread practice. The repair and strengthening of deteriorated and damaged infrastructure has become one of the most important challenges that authorities face. For instance, in many countries the need for rehabilitation of existing structures is growing, especially in developed countries with their infrastructure built in the first half of the last century. Many of the structures that were built after World War II had little attention to durability issues. These structures are now in need of urgent repair and retrofit. (L.C.Halloway 2010).

The FRP materials can also be used instead of steel rebars as reinforcement in reinforced concrete structures and pre-stressed concrete structures. FRP rebars can resist oxidation and corrosion from sea-water, de-icing salts and the abrasive environment. They have a better strength to weight ratio than steel. The world's first highway bridge which was constructed by using FRP instead of steel rebar was in Germany in 1986. Nowadays there are hundreds of constructed or in construction projects over the world mostly in North America and Japan with FRP rebars instead of steel.

As it was mentioned, composite cable applications in the infrastructure are used in the construction of suspension and stay cables for bridges, pre-stressed tendons for various concrete structures and external reinforcements for structural beams. All these applications require materials that incorporate high tensile strength and, in addition, require characteristics such as corrosion resistance and light weight. (L.C.Halloway 2010).

As it was mentioned, one of the applications of FRP martial is in bridge construction. FRP material can be used in different parts of bridges. FRPs can also be used in construction of whole FRP bridges. . One of the first examples is Tech 21 Bridge in Ohio United State. This bridge was the first fully composite vehicular bridge in the USA. Due to light weight of structure, compared to its concrete counterpart, the structure was installed in just 6 weeks (Friberg and Olson, 2014).This two lane bridge has a length of 10 meters and is 7.3 meters wide.

The first all composite bridge in Europe was constructed 5 years after the first one in USA and in England. Mill Bridge was constructed in 2002.The Mille Bridge has the

10 meter span and 7 meters width. A series of load tests were performed on the bridge during 8 year period (Friberg and Olson 2014).The first test was performed after the construction, the second one was conducted three years after construction and the last test was done eight years after construction (Canning, 2007).The load tests were carried out by passing a military tank over the bridge in order to control the static deflections and the dynamic performance and creep behavior (Canning, 2007) .The results of all tests were all positive and reasonable.

Another project was conducted in 2004 in Spain. This bridge was the first highway composite bridge in Europe with the 46 meters length and 8 meters width. In the bridge trapezoidal cross sections was made by fully FRP composites (Friberg and Olson 2014).

Manufacturing of FRP using glass and carbon fibers in combination with epoxy and vinylester resins is very common construction. In most of the applications, glass fiber reinforced polymers (GFRP) are used due to their comparatively low cost. The Glass fibers however have relatively low elastic modulus and exhibit some durability concerns in alkaline environments. The Carbon FRPs have relatively high elastic modulus, comparable to steel, and are more attractive but more expensive. The Aramid FRPs are sensitive to creep and also display poor durability characteristics and more susceptible to moisture absorptions. The Aramid FRPs also perform poorly at high temperature.

Figure 5 Bridge with FRP deck during construction and after compilation.

2.4 Design approaches

During the recent years different committees have prepared design guidelines for FRP construction. However, at present there is no accepted official international codes available to design FRP composites for infrastructure applications (Friberg and Olson, 2014). One of the guidelines is the European approach from the European standard polymeric Composites Group (EUROCOMP). The first version of EUROCOMP was written in 1996 based on scientific researches which were conducted before 1996. In EUROCOMP compilation there was a try to depict it like Euro code and in order to make it more useful for designer and engineers that have been working with Euro code. In the EUROCOMP connections are considered separately and not as an entity (Cholosta 2012).The other guidelines that contain the valuable recommendation and useful information on connections are BD 90/05 standard, Fiberline design manual and also Design guide for FRP connection written by Mosslam. (Mosallam, A. S., & Knovel, 2011).

American society of civil engineering realizes two design approaches for connection namely (1) allowable stress design approach and (2) load resistance factor design (LRFD). The Eurocomp (Structural design of polymer composites deign code and handbook) presents four different approaches for designing connections as (1) simplified procedure (2) rigorous procedure (3) design by testing and finally (4) numerical method.

Allowable stress design which was popular and was used for decades in civil engineering aspects has been recently replaced by LRFD approach. In the allowable design approach only one safety factor (SF) is in use and it is not sophisticated enough to weight all effective parameters. Whereas in LRFD method a better estimation of applied loads and also expected strength of particular member is weighted and is under consideration. The EUROCOMP design code and handbook published in 1996 adopted the LRFD approach.

Base on the EUROCOMP design code simplified and rigorous procedures can only be used to a limited number of joint whereas, the testing approach can be used and applied for all connection. In general, based on EUROCOMP design code or other codes a connection should be designed for resistance and should be effective enough to work properly in its intended life.

3 Connections

It is expected that by improving the knowledge on FRP connections, the application and use of FRP as a new material with anisotropic properties for different purposes become more facile. Most of the time FRP elements and especially structural pultruded seems similar to steel profiles and the connection between these elements seems to be similar as steel connections. In the review it will be seen that FRP connections are similar to steel elements connections in general, although there are important differences between them.

As it was mentioned earlier one of the unsolved questions for extended usage of FRP materials is the lack of the knowledge about connection's behavior. For instance, a recent feasibility study at Chalmers University of Technology indicates that the FRP panels can be used in underground culvert bridges and they can work properly. But the study does not cover the assembling issues and also information related to connections. In the following parts ,more general information about different kinds of connection in FRP will be discussed.

EUROCOMP has classified FRP connections into three main groups based on importance as

- Primary structural connection
- Secondary structural connection
- Non-structural connections

And also has divided joint categories base on joining techniques in three different categories as

- Mechanical connection
- Bonded or adhesive connection
- Combined connection

3.1 Joint categories and joint technique

In this part a general overview about different kinds of connection will be discussed and in the following parts each kind will be discussed more in detail.

As it was mentioned before the EUROCOMP code has classified FRP connection into three groups as

- Mechanical connection
- Bonded or adhesive connection
- Combined connection

The Mechanical connections are defined as shear loaded fasteners or axially loaded fasteners like bolts, rivets, contact strap and embedded fasteners (EUROCOMP). The research work on using mechanical joints especially bolted joints for FRP began in aerospace industry in the mid 1960s (Mosallam , & Knovel 2011) .

The EUROCOMP guideline categorizes bonded connection like adhesive bonded joints, laminated joints, and moulded joints, bonded insert joints and cast in joints in the bonded or adhesive connection group. The Adhesive connection is realized as the most common method of connection in FRP material (Mosallam, & Knovel 2011).

The adhesive joints in essence transfer loads as shear forces while holding the geometry of the shape (Mosallam, & Knovel 2011).The Stress concentration in adhesive connection is less compared to bolted and other mechanical connections. The catastrophic failure or brittle failure is expected when brittle adhesives are used. Another problem which is expected in these kinds of connections is expected when using ductile adhesive. In this case creep is a problem and may occur. Usually in these kind of connections adhesive is known as the weak link in the joint (Mosallam, & Knovel 2011) and it is not fit with the philosophy of designing the connections. However, efforts have been made to ensure that failure in the adherent precedes failure in the adhesive (Mosallam, & Knovel 2011).The adhesive strength is a function of percentage of void, thickness variation, environmental effects, processing variation, deficiency in surface preparation and other factors that are not always properly controlled (Mosallam, & Knovel 2011). The adhesive connection needs special treatment and also is sensitive to environmental conditions. The structure cannot be loaded directly after using the adhesive and the adhesive material needs a certain time for chemical reaction. Regardless of time these kinds of connections are also sensitive to the temperature and humidity. For instance, a rigid epoxy provides high strength at room temperature, but essentially no strength at -23 C or 177C (Mosallam, A. S., & Knovel 2011).

Based on the EUROCOMP categorization the third group of connection is combination of the first two kinds and it was named as combine connections. The combined joints are known as bonded-bolted and bonded-riveted joints. It is expected that by combination of these two methods a better mechanical performance would be obtained. In this kind of connection a better strength and fatigue life is expected .on the other words the superposition of the stiffness and strength and also fatigue life is bigger in these kinds of connections. The analysis and design of combined joint is very complex and requires using nonlinear techniques (Mosallam& Knovel 2011).

The table 9 shows a comparison of three joining methods.

Table 9 General characterization of different connections. (EUROCOMP).

Characteristic	*Mechanical*	*Adhesive*	*Welded*
Stress concentration at joint	*High*	*Medium*	*Medium*
Stress to weight ratio	*Low*	*Medium*	*Medium*
Use with non-rigid polymer	*Inserts required*	*Yes*	*Yes*
Seals assembly (water tightness)	*No*	*Yes*	*Yes*
Thermal or electrical insulation	*No*	*Yes*	*Yes*

Attractiveness	*Bad*	*Good*	*Good*
Fatigue endurance	*Bad*	*Good*	*Good*
Sensitive to peel loading	*No*	*Yes*	*No*
Disassembly	*Possible*	*Impossible*	*Impossible*
Inspection	*Easy*	*Difficult*	*Difficult*
Skill required fabricator	*Low*	*High*	*High*
Heat or pressured required	*No*	*Yes*	*Yes*
Tooling cost	*Low*	*High*	*High*
Time to attain ultimate strain	*Instantaneously*	*Long*	*Short*

Typical joint configurations are shown in the figure 6.

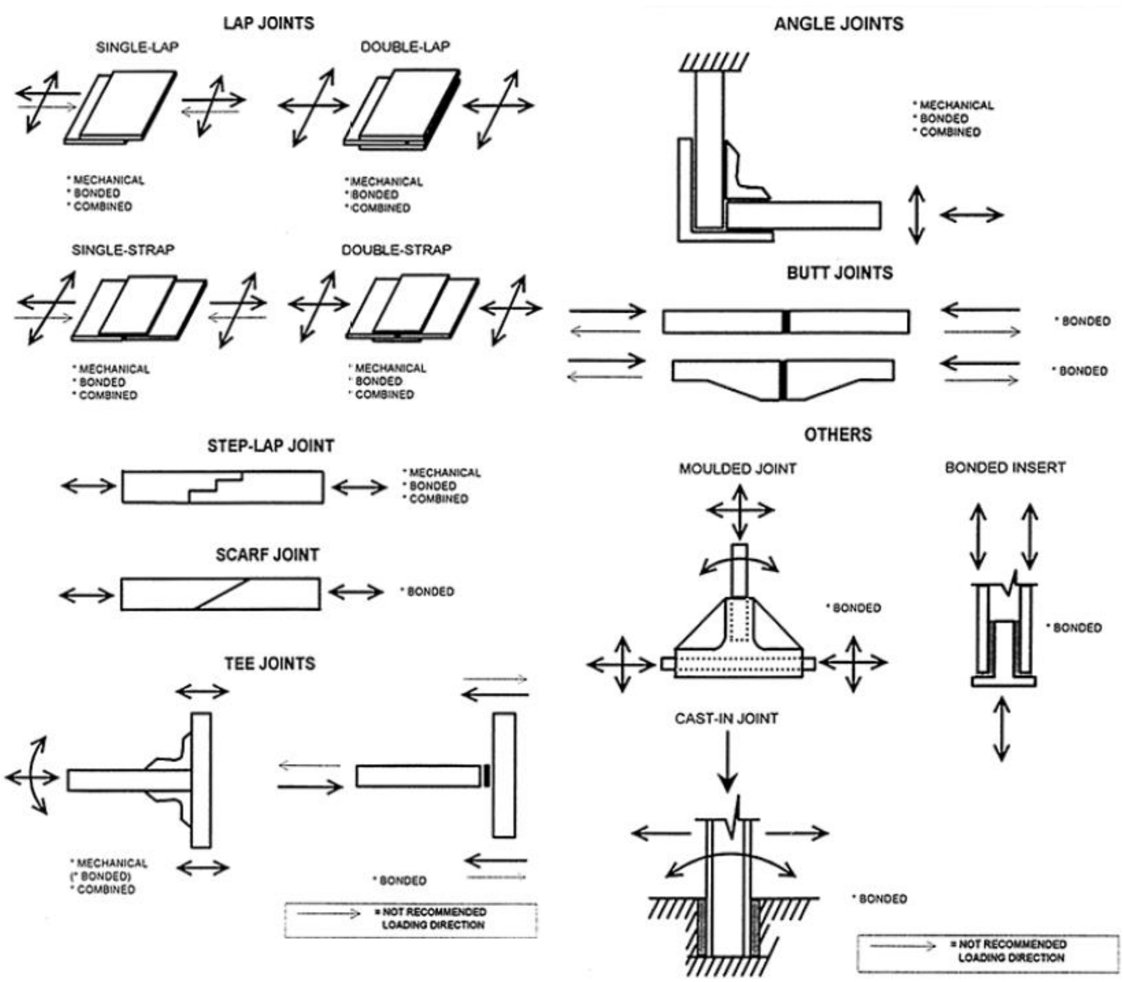


Figure 6 Joint configurations, (EUROCOMP).

The Pros and cons of different kinds of connection are presented in the tables 10. The most challenging issue in mechanical connection can is the stress concentration problem while the easy assembly without need of preparation is the advantage of such joints.

Table 10 Pros and cons of mechanical connection.

Mechanical Connections	
Advantages	*Disadvantages*
Requires no special surface preparation	*Low stress or stress concentration*
Can be dissembled	*Special practice required in assembly; results in time consuming assembly*

Ease to inspection	*Fluid and water tightness*

In the bonded connections, the high strength is an advantage while surface preparation and curing time is considered as a negative aspect. Table 11 shows the most important pros and cons of bonded connection.

Table 11 Pros and cons of bonded connection.

Bonded Connections	
Advantages	*Disadvantages*
High joint strength can be achieved	*Cannot be disassemble*
Low part count	*Required special surface preparation*
Fluid and weather tightness	*Difficulty to inspection*
Potential corrosion problems are minimized	*Temperature and high humidity can effect joint strength*
Smooth external surfaces	

The prediction for the behaviour of combined connections is hard ,moreover the avalible information about the combined connection is not too much available for structural enginnering.Howevr, it is expected to have a better performance from the structural point of view.

The advantages of combined connection is shown in the table 11.

Table 11 Pros and cons of mechanical connection.

Combined Connections	
Advantages	*Disadvantages*
Bolts provide support and pressure during the assembly and curing	*Structurally bolts work as back up in an intact joint, bolts carry no load*
Growth of bond line effect is hindered by bolts	

4 Behavior of connections

4.1 Mechanical connections

Self-tapping screw, rivets and also bolts connection are the common forms of mechanical connectors. The Self- tapping screw is known as the simplest form of mechanical connectors and is very efficient when the access to the other side of FRP plate is impossible (Mosallam& Knovel, 2011) .The rivets are known mostly as good connectors for plates less than 3 mm thick however; in the thicker plates using rivets it is not advisable. The clamping pressure resulted from rivets is not ideally controllable and the process of riveting can damage the FRP internal structure. The bolted connection is one of the best forms of mechanical joining for FRP materials and is the most common type used in civil engineering applications. This kind of connection has been used in FRP trusses, beams, and braced frame structures, as well as multicellular FRP bridge deck structures. In the connection both metallic (usually galvanized or stainless steel) and FRP bolts can be used as fasteners (Zoghi, 2013). Unlike adhesive connection brittle failure is not likely in this kind of connection. The stress concentration is great deal in this kind of connection. Since the FRP materials are anisotropic, the stress concentration at a circular hole can be as 8 times bigger than the average stress, compared to 3 times of average stress for isotropic materials like steel (Collings, 1987).

In the FRP bolted connection the failure modes are similar to steel mechanical connections, however, the mechanism of the damage and failure initiation and propagation are basically different. The nominations of different parameters in a mechanical connection are shown in figure 7.

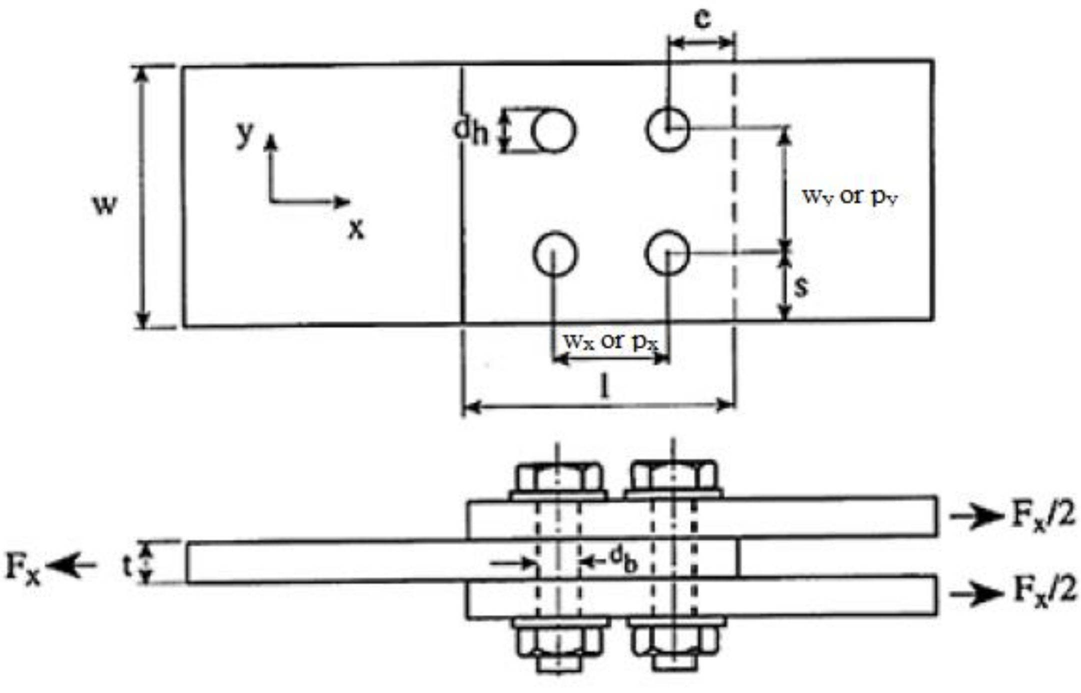


Figure 7 Nomination of different parameters, EUROCOMP.

The mechanical joints are classified according the way that it transfers loads. One connection can transfer loads in shear or tension or combination of shear and tension.

The Shear loaded fasteners are also dividing into two groups base on whether the applied load is acting eccentrically or concentrically.

The figure 8 shows the three load transfer mechanisms in mechanical connections.

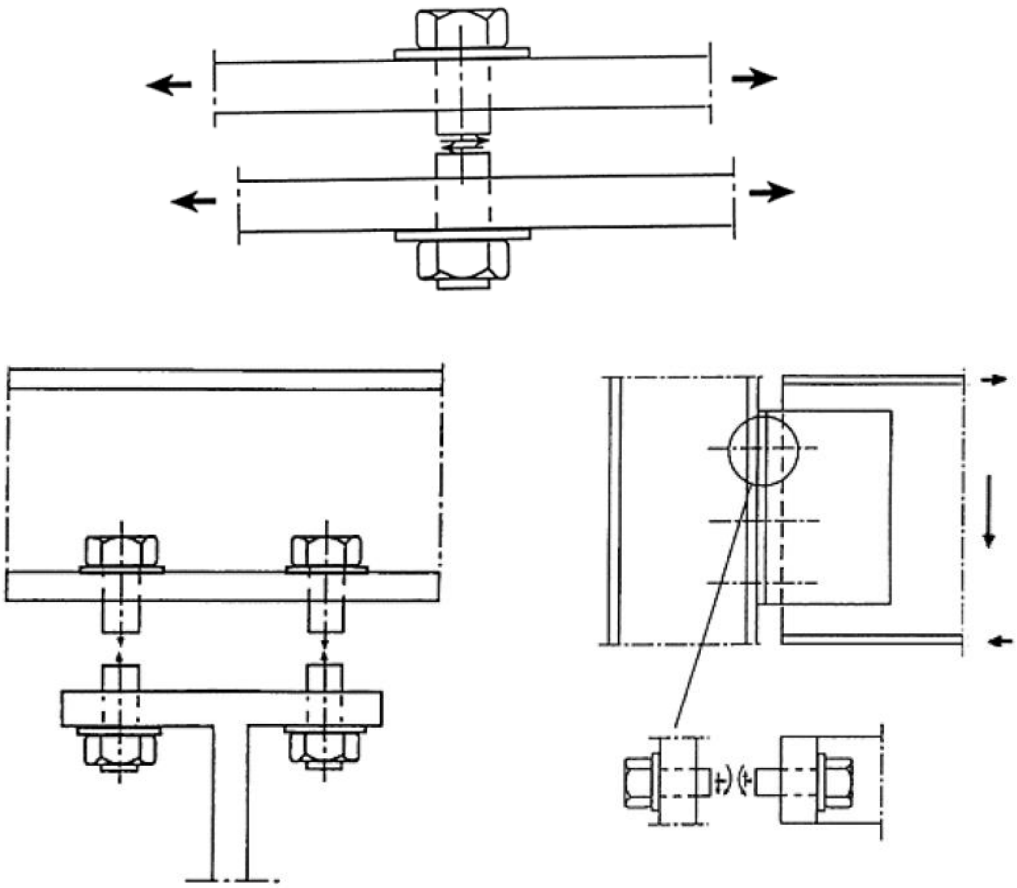


Figure 8 The Load transferring in a connection, (Mosallam & Knovel 2011).

The EUROCOMP design code has suggested that several parameters should be considered in mechanical connections including

(a) Design parameters

- Geometry (width (w), spacing (w_y or p_y) , edge distance(e), side distance(s), hole pattern, etc.)
- Hole diameter (d_h) and bolt size(d_b)
- Joint type (single lap, double lap, etc.)
- Plate thickness
- Loading condition (tensile, compressive, shear, etc.)

(b) Material parameters

- Fiber form and type
- Resin
- Fiber orientation
- Form of construction (e.g. solid laminate, sandwich construction, etc.)
- Stacking sequences

- Fiber volume fraction
- Fastener material

(c) Fastener parameters

- Fastener type (screw, fastener, rivet, etc.)
- Clamping force
- Washers
- Fastener and hole size

(d) Long term and environmental exposure factors

- Creep and creep rupture
- Humidity
- Temperature
- Load cycling
- Chemical attacks
- Stress corrosion and etc.

4.1.1 Failure in mechanical connections

The failure in the mechanical connection even in the FRP material is not sudden and this is one of the priorities and benefits of the using the mechanical connection, in other words, the warning before the failure is known as a great benefit of mechanical connections.

The Composite joints subjected to compression are less sensitive to joint geometry (edge, distance, width and thickness) and are generally stronger than joints subjected to tensile forces (Mosallam& Knovel, 2011). For this reason the bolted connections in tension are in more focus than joints in compression mode.

In the FRP mechanical connections there are two important limitations compared to steel mechanical connections. The conventional fully plastic method of designing metallic bolted joint is not valid in FRP connections. It is common in FRP connection that failure takes place at 2% strain however; in the ductile metal the expected strain is much larger than 2 percent and this ductility cause drastic load distribution between different fasteners.

In the connections subjected to tension seven probable failures is expected as following

1- Bearing failure
2- Shear out failure
3- Net tension failure
4- Cleavage/tension failure (tension and shear out failure)
5- Bolt failure
6- Punching failure
7- Combination of the modes 1-6

Figure 9 shows the different modes of failure in the bolted connection.

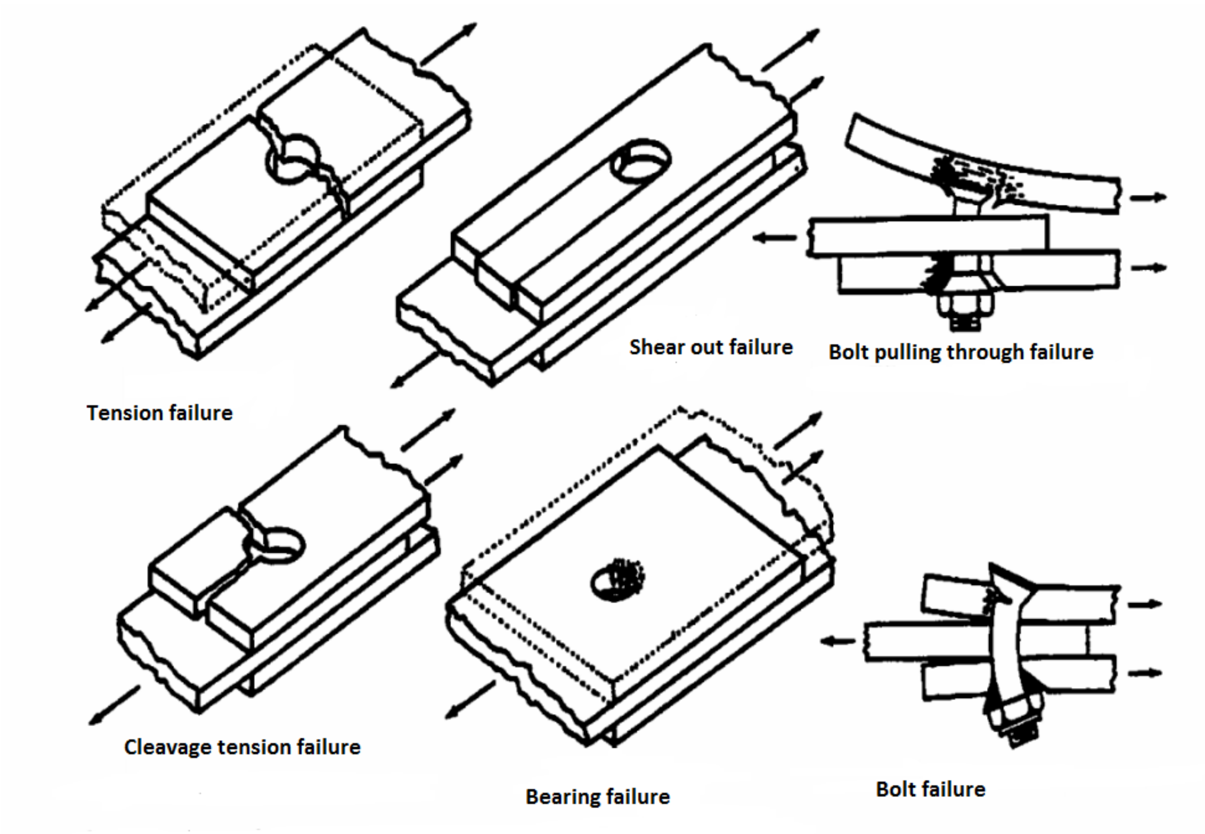


Figure 9 Common failures in bolted connection, (Mosallam, & Knovel 2011)

EUROCOMP suggests that failure analysis shall be based on detailed of stress distribution around the fastener holes. Moreover, the EUROCOMP design suggests that the failure analysis shall evaluate in four modes as net-section, bearing, and shear-out and fastener shear failure in the mechanical connections. In the following sections the most common forms of failure is going to be presented more in detail.

4.1.1.1 Bearing failure

Among different modes of failure the bearing failure mode is less catastrophic and the least possible mode of failure. However, in order to ensure an efficient bolted design, the bearing strength should be kept as low as possible on the most critical fastener in the composite structures (Mosallam & Knovel, 2011) .Reaching the ultimate Bearing compression strength on the loaded on the half of the bolt, is the reason for this kind of failure, hence compressive strength of the zero degree fibers as well as the clamping pressure are important parameters in determining bearing strength (Collings, 1977). Several factors affect the joint bearing strength. For instance, increasing the clamping torque and using the adequate washer diameter will increase the joint bearing strength (Mosallam, A. S., & Knovel 2011) .The fiber direction and shape of orientation of them is also affecting the bearing strength.

In order to prevent the bearing failure mode it is recommended to use weaker bolts which are more compatible with limited bearing strength of lamented FRP material. Using the stronger fastener is not fitted well with FRP composite material. It is also recommended to use more numbers of small diameter bolts rather than a few numbers of larger bolts (Mosallam, A. S., & Knovel 2011) .The ASCE plastic design manual also suggests bearing strength as the average bearing stress at the deformation of 4%

of the bolt diameter. Regardless of what was mentioned above, some joint geometrical parameter have great impact on the joint bearing strength ,while others have minimal or do not have effect.(Mosallam, A. S., & Knovel 2011) .For instance, the increase in the hole diameter to thickness ratio $\left(\frac{d}{t}\right)$ will results on an appreciable decrease of bearing strength of connection (Mosallam, A. S., & Knovel 2011), while the other geometrical parameters, such as edge distance to hole diameter ratio $\left(\frac{e}{d}\right)$ and joint width to diameter ratio $(\frac{w}{d})$ control the ultimate failure mode of the joint and they have little influence on joint bearing strength (Mosallam, A. S., & Knovel 2011) .

An average bearing stress assumed to act uniformly on the cross sectional area of the hole in the uniaxial loading can be calculated from.

$$\sigma = \frac{P}{n * d * t} \qquad (4.1)$$

σ, average baring stress

P, load

n, Number of bolts

t, thickness of the section

d, bolt diameter

4.1.1.2 Net section failure

The net section tension strength in bolted connection is dependent to the geometry of a connection and also the tension strength of material. This kind of failure is more probable when hole diameter to width ratio is large and bypass to bearing load ratio is high. Moreover, in essence this mode of failure is brittle.

Net section failure is transverse to the direction of the connection force. It causes primarily by tangential tensile or compressive stresses at the hole edge and for joint subjected to the axial load, occurs when the ratio of by-pass load to bearing load is high, or when the ratio of the hole diameter to plate width $\left(\frac{e}{d}\right)$ is high.(EUROCOMP)

The average net stress σ_n or net stress across a section can be define easily as

$$\sigma_n = \frac{P}{(w - nd) * t} \qquad (4-2)$$

Where

P, tension force

w, width

n, bolts

d, diameter within the section.

However to the basic formula above, it is more logical not to ignore the effect of stress concentration

$$\sigma_{\ n} = k_{te} \frac{P}{(w - nd) * t} \qquad (4-3)$$

The k_{te}, is defined as elastic concentration factor which is related to maximum stress adjacent to the hole. This factor is known as elastic isotropic stress concentration factor also. This factor only is recommended in the net tension failure mode.

The behavior of bolted connection in tension is not like steel bolted connection. In the steel bolted connection is expected that by deformation and yielding some stress concentration diminishes, whereas in the FRP bolted connection the behaviour of connection is quite linear elastic until failure and high stress concentration is expected on the connection. The Stress concentration factor or k_{te}, was defined by Hart-Smith (1994). The Stress concentration factor for net tension failure was defined on that research in two kinds of single bolted joint and multiple bolted joint both in loaded and unloaded cases.

For Single bolted joint,

- Loaded hole:(most of the time θ can be ignored in this case)[1]

$$k_{te} = \frac{w}{d} + \frac{d}{w} + 0.5\left(1 - \frac{d}{w}\right)\theta \approx \frac{w}{d} + \frac{d}{w} \qquad (4-4)$$

Where $\theta = \left(\frac{w}{e} - 1\right)$ for $\frac{e}{w} \ll 1, \theta = 0$ for $\frac{e}{w} \gg 1$ $\qquad (4-5)$

- Unloaded hole:

$$k_{te} = 2 + \frac{d}{w} + \left(1 - \frac{d}{w}\right)^3 \qquad (4-6)$$

For multiple bolted joints with identical holes:

- Loaded hole:

$$k_{te} = \frac{p}{d} + 0.5\left(1 - \frac{d}{p}\right)\theta \approx \frac{p}{d} \qquad (4-7)$$

$$\theta = \left(\frac{p}{e} - 1\right) \text{ for } \frac{e}{p} \ll 1 = 0 \ for\ \frac{e}{p} \gg 1 \qquad (4-8)$$

- Unloaded hole:

$$k_{te} = 1 + 2\left(1 - \frac{d}{w}\right)^{\frac{3}{2}} \qquad (4-9)$$

Where

θ ,a non-dimensional factor which is a function of e/w in the case of single bolted joints and a function of p/e for multi bolted joints

p, is defined as hole pitch or on the other words the distance between the bolt holes centerlines.

As stated before, the tensile strength is highly dependent to fiber orientation. The fiber parallel to the load carry most of the load, and for CFRP, failure is initiated at the stress concentration at the edge of the hole which is perpendicular to loading axis. (Potter 1978). The behavior of GFRP is expected to be more complex under tension.

[1] Formula from Hart-Smith(1994)

It is expected that the complex combination of shear and tension causes failure. The concentration factor that defined previously can also affected by fiber orientation in ultimate failure of a composite. The Hart-Smith report defined stress concentration factor for ultimate failure which is fiber orientation dependent as

$$k_{tc} = C(k_{te} - 1)+1 \tag{4-10}$$

Where C as stress concentration coefficient factor is defined in table below and for brittle material C = 1 was recommended. For ductile material the C coefficient is more close to zero. For instance, for aluminum C = 0 was recommended by Hart-Smith report.

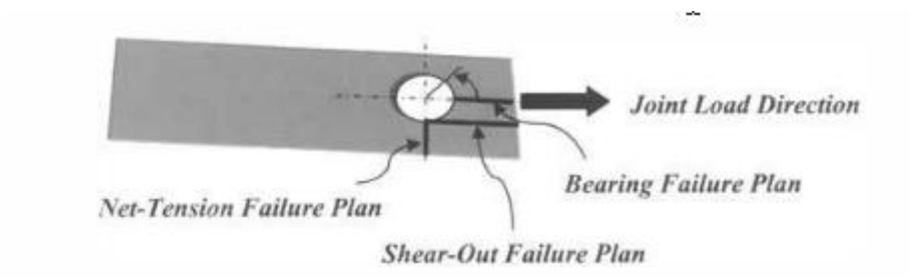
Table 12 Stress concentration coefficient

Fiber orientation degree	C factor
0	0.33
45	0.21
90	0.25

It should be noted that, in the case of having the Aramid fibers, the Aramid fiber has low lateral adhesion strength in compare to high tensile strength and tends to split along the fiber axis. This relieves the stress concentration at the hole edge and contributes to the tensile strength of the connection (Colling 1987).

4.1.1.3 Shear out of failure

The Shear out of failure is happening when the shear stress is affecting the connection and take places along out of plane on the hole boundary in the principal fastener. Most of the time shear out failure is a consequence of bearing failure because of short edge distance, however, it also is probable in highly orthotic laminated and it is independent of the end distance. The shear out of failure is a combination of in plane and interlinear shear failure. It should be noted that the bolt shear out failure which is caused by high shear failure in the fastener is quite rare in FRP material.



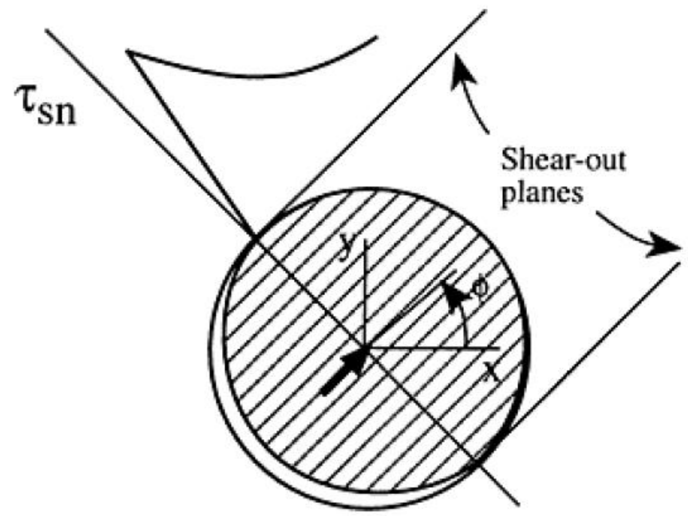


Figure 10 Shear out failure, (Mosallam, A. S., & Knovel 2011)

In order to prevent the shear out failure in the FRP composites optimization of fiber direction is indispensable. This optimization is necessary especially in the parts at the connection zone. The shear-out failure is more common for fiber pattern that are both rich in 0 degree piles and deficient in 90 degree piles .In should be noted that the most pultruded commercially manufactured are unidirectional and the bidirectional ones are rare.

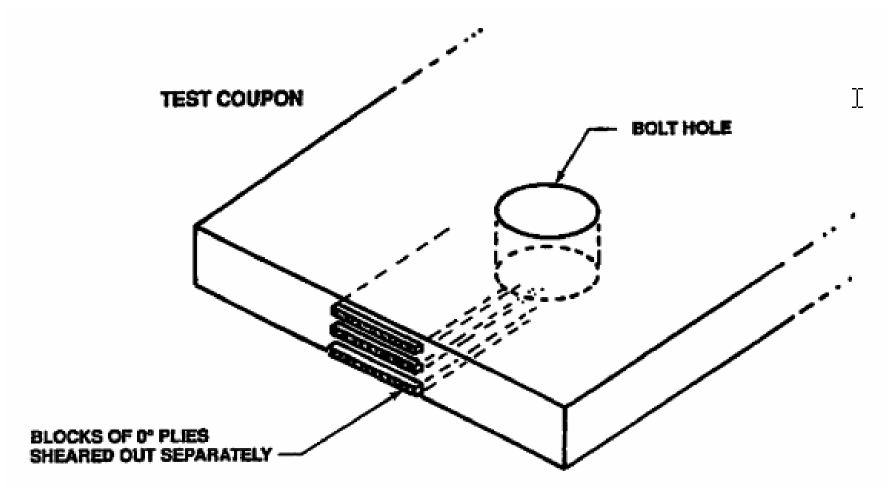


Figure 11 Shear out failure, (Mosallam, A. S., & Knovel 2011).

It is clear that in order to prevent shear out failure the shear strength of material should be more than shear force. The shear stress or τ produce by force P is calculated from the same way that it is calculated for isotropic material.

$$\tau = \frac{P}{2et} \qquad (4-11)$$

4.1.1.4 Cleavage tension failure

Cleavage failures is another form of low strength failure resulting from the too-close proximity of the end specimen (Mosallam, A. S., & Knovel 2011).This type of failure is started at the joint end rather than adjacent to the bolt hole (Mosallam, A. S., & Knovel 2011).In this kind of failure the combination of tension and shear is the reason of the failure. Most of the times the cleavage is starting from by incomplete net tension failure.

In summary, the cleavage failure can be avoided by selecting the appropriate edge distance and by optimizing the joint member laminate architecture which should contain an adequate percentage of transverse 90-degree piles (Mosallam, A. S., & Knovel 2011).

4.1.1.5 Bolt pulling through laminated failure mode

This kind of failure takes places for connections with sufficiency large thickness to bolt hole diameter($\frac{t}{d}$). In this case the bolt head is pulled through after bolt bending (Mosallam, A. S., & Knovel 2011). The rivet in FRP material mostly is using in the single shear mode and bolt pulling through laminated failure is common on them. The bolt pulling through is a function dependent to the washer diameter. The figure below shows this kind of failure effective parameter and mechanism more clear.

$$N_{sd} \ll f_{V,Rd} * \pi * d_r * t$$

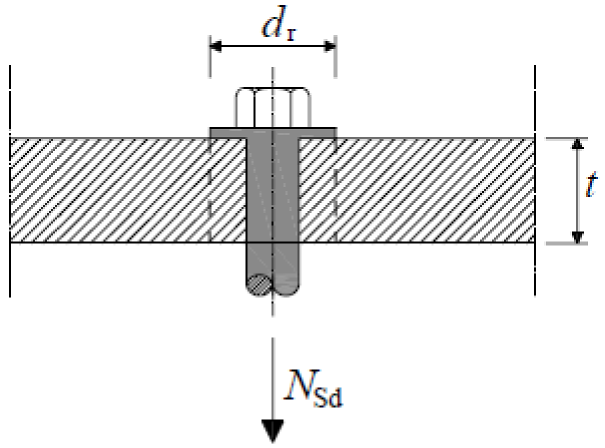


Figure 12 Bolt pulling through failure, EUROCOMP

4.1.2 Effective parameter in mechanical connection

As it was mentioned in the in the introduction of mechanical connection several parameters are effective in connections and joint strength. The effective parameters were divided there in five main groups. In the following part of this report influential parameters are explaining and discussing more in detail in mechanical joints.

4.1.2.1 Thickness

The effect of joined member thickness ,t, is usually expresses as a ratio of the hole diameter to thickness (Mosallam, A. S., & Knovel 2011).The ratio of (d/t) is s suggested to be greater than one in order to decrease the possibility of bolt failure. The joint ultimate bearing strength increases with decreasing the (d/t) ratio (Mosallam, A. S., & Knovel 2011).Based on this fact, the designer should try to use smaller (d/t) values, nothing that a lower limit exists below which fasteners would fail in shear (Mosallam, A. S., & Knovel 2011).

The amount of this value varies in each reference or recommendation. The design guide for FRP connection has recommended not using this ratio less than 1,2. The EUROCOMP DESIGN code has limited this value between 1, 2 to 1,5.

Then number of publications and researches including the effect of thickness and have focused on thickness effect are not too many. Between them Colling and Mathews have mentioned about the effect of thickness better than others.

4.1.2.2 Width

Regardless of the (d/t) ratio which has influence in FRP connection, the hole diameter to joint width ratio is important and effective. The bearing failure takes place in composites joints with small hole diameter to joint width ratio (Mosallam, A. S., & Knovel 2011). In general, it is expected that by increasing the value of the w/d the joint stiffness increases also. By changing the member width and when it is increasing the mode of failure also will change from bearing to the net tension failure. Some experimental results suggest that there is not clear point for changing the failure mode from one to the other failure mode in this case and as it was mentioned instead of a point of transmission considering a region of transmission is more acceptable. (Mosallam, A. S., & Knovel 2011).

Between the different kinds of failure net tension failure is highly dependent to the width. Hence, the FRP material cannot reduce stress concentration by help of plasticity like what happens in metal connections. The effect of width is most marked for laminated with high proportion of zero fibers and least for 45 fibers laminates. (Collings 1977).

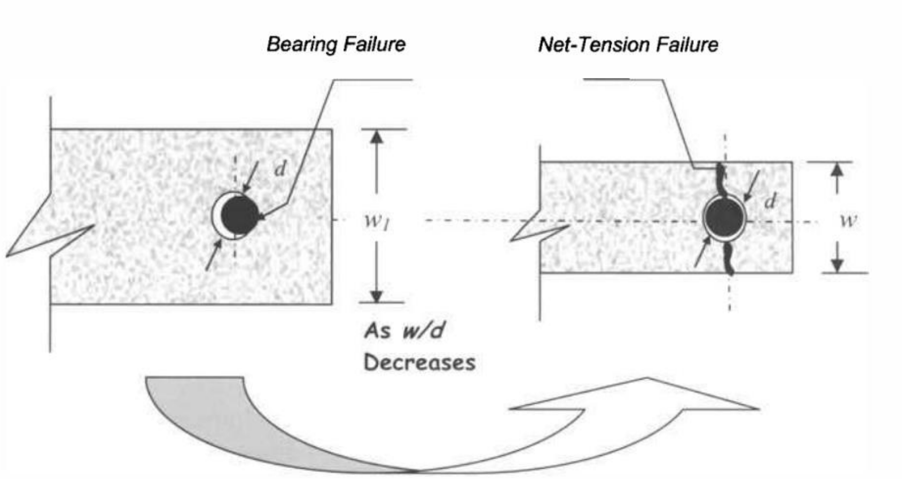


Figure 13 Bearing failure versus Net-Tension failure, Mosallam, A. S., & Knovel 2011)

4.1.2.3 Edge distance

The $\frac{e}{d}$ ratio is the other effective parameter for composite joint strength. The edge distance or, e, is the distance from the corner hole centre to the edge. In the case that e/d ratio decreases the failure mode changes from bearing mode to the shear out failure mode. There is a difference between this kind of situation in the FRP composite with other material like steel in the similar case, hence, the shear out failure results from unsatisfactory fiber pattern and is not because of shorter edge dimension.

The design guide of FRP connection (Mosallam, A. S., & Knovel 2011) has mentioned that by increasing the edge distance until it equals to the bolt pitch, an appreciable increase in both bearing and tensile strength is expected ,but it does not mean the enough resistance to shear out failure is happening. One of the researches about the effect of edge distance was conducted by Hart-Smith. They have reported that a minimum value of the e/w is required to develop full net section strength. In order to that research, edge distance must be greater than or equal to the side distance (EUROCOMP).

4.1.2.4 Pitch or bolt spacing

In order to use the full strength of all bolts minimum distance between the connector should be defined properly. The distance between the connectors also is defined as a ratio of fastener diameter in most of the materials. The Design guide for FRP connection (Mosallam, A. S., & Knovel 2011) suggests five for (p/d) ratio as the optimum value. The back pitch ratio is affecting by fiber orientation and also was one of the objectives of some different researches.

The researches which were conducted by Godwin and Matthews 1980, Kretsis and Matthews 1985, Wong and Mathews 1981 proved that unlike the metal connections the multiple rows fastener are not effective in FRP material. The reason of this event might come from using the forcing fiber at the bolt hole and inability to re-establish untouched capacities between the rows. The figure 14 show the limitation of center to center spacing for one or two rows bolts. The Part A in the figure below indicates geometry for tension failure and the part B in the figure 14 indicates single row joint geometry for bearing failure. The Part C in the figure 14 is showing the geometry condition in the two row joints for bearing failure.

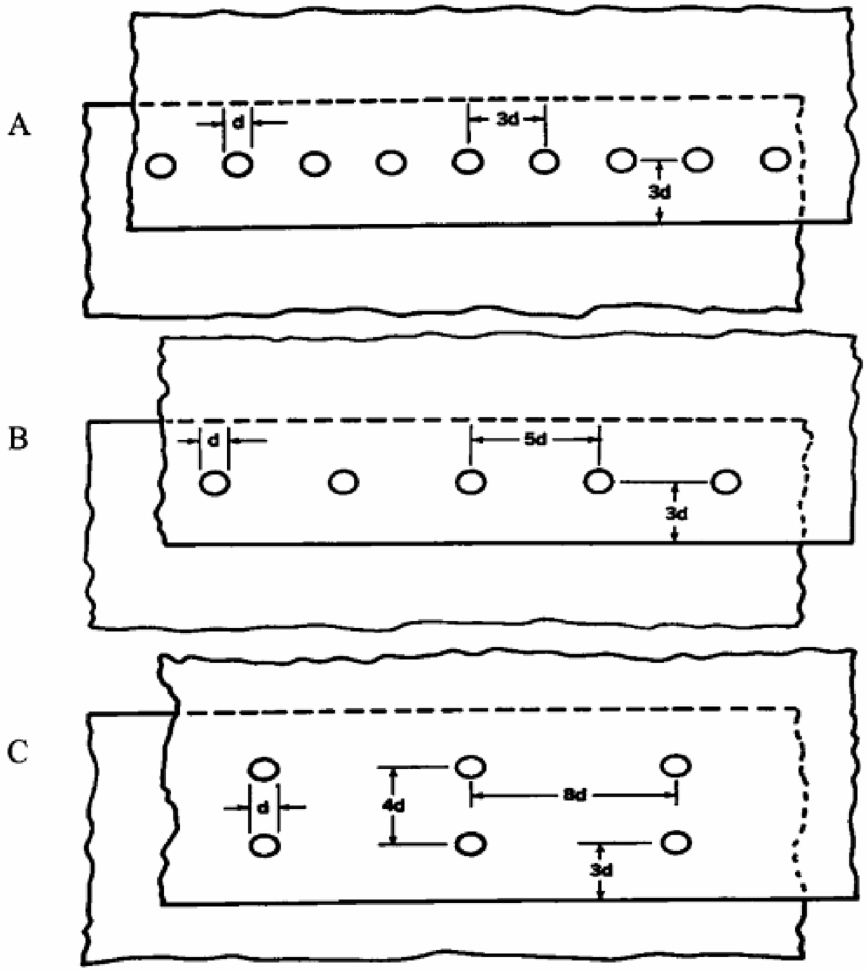


Figure 14 *Bolts center to center recommendation, Mosallam, A. S., & Knovel 2011.*

A. Single row joint geometry for tension failure

B. Single row joint geometry for bearing failure

C. Two row joint geometry for bearing failure

4.1.2.5 Fiber orientation effects

As it was mentioned before FRP are fiber oriented materials and anisotropic, moreover, the fiber orientation is affecting the connection joint strength and failure mechanism as well. It is expected that the maximum strength of bolted joint achieves when the direction of applied load coincides with the direction of maximum load. Or on the other words, the most efficient lay up for mechanical fasteners are those that are nearly quasi-isotropic, as opposed to those that are highly orthotropic (Mosallam, A. S., & Knovel 2011).

The highest bearing strength is attained with lay-ups containing about 50% of degree piles. When 45 degree piles are added to this fiber architecture, an improvement in the compressive strength of the concentrated 0 degree piles is expected (Mosallam, A. S., & Knovel 2011). In 1977 Colling showed that, the best joint performance for CFRP is possible when the combination of 0 and 45 degree applied. The figure 15 shows that the place for shear failure dominant at 45 degree (Dat2000). When the degree increases the shear strength increases also and the bearing failure becomes the critical mode of failure (Dat 2000).

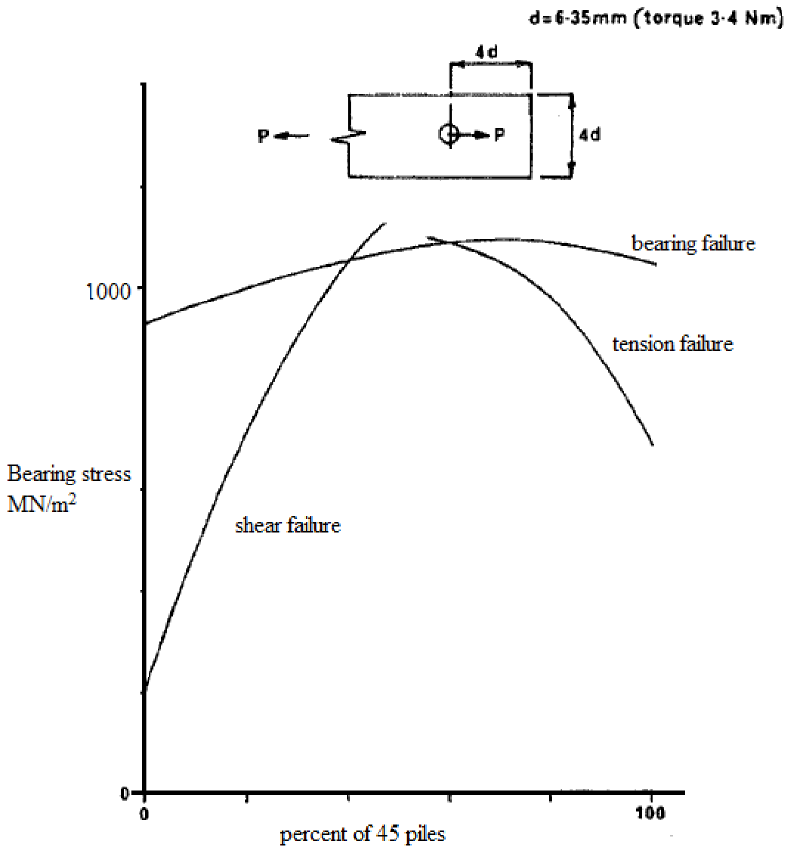


Figure 15 Influence of CFRP fiber orientation on failure mode, Dat Duthinh 2000

The figure 16 shows the fiber effect in the different clamping mode. It is obvious from the figure that the pre stressed bolted connection are less susceptible to fiber directions, whereas the pin bolted connection are more susceptible.

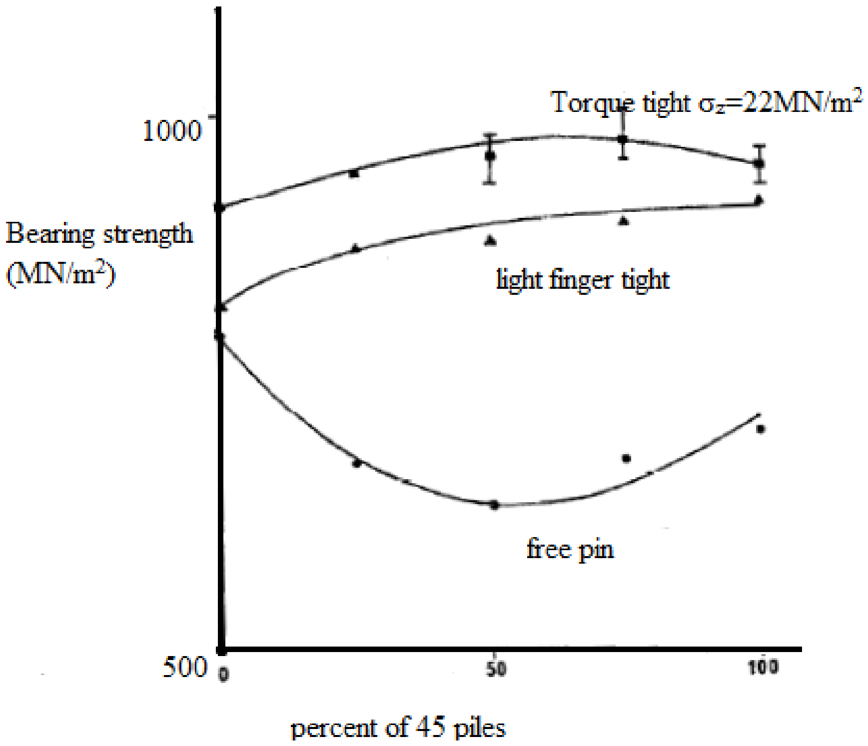


Figure 16 Effect of clamping pressure on the bearing strength from Colling 1982.

One of the best experimental researches on the effect of the orientation was conducted in 1996 by Prabhakaran. The further researches which were done for instance by Turvey also confirmed the result of Prabhakaran try. The Prabhakaran research was conducted on 105 numbers of specimens from E glass. Three pined loaded joints were tested for angles between 0 to 90, the changing steps has been set with the 15 degree.

The following conclusions were drawn from that study.

1- The tensile strength is increasing from 0 until 45 degree and the maximum strength will be getting on 45 degree. The tensile strength after 45 degree is not too much sensitive to the angle however it decreases.
2- Dual fracture modes were observed because of the dual laminate structure
3- When the angle of fiber orientation is increasing from 0 to 90 the joint bearing strength decreases. Thirty percent of degradation is expected on the 60 degree in compare to $\theta = 0$. This part was fitted well with the results from Mallick and Little report (1985).
4- Shear out strength was observed the minimum amount at the $\theta = 75$,with the 28% reduction.
5- Initiated cracks at the hole and propagated along the roving is accelerator for the ultimate failure of the joints.

6- A sharp drop with 60% degradation was observed in the joint net-tension at $= 30$. Although it was observed that the net tension strength was not sensitive to angle orientation up to 90 degrees.

The ductile or brittle failure is quite important parameter in designing of connection. One of the researches which was conducted on connections and reported about the effect of the fiber orientation on ductility of a connection was conducted in 1996 by Yuan. It was reported that fiber orientation less than 45 is susceptible to ductile failure, while the brittle failure was observed for joints with larger than 45 degree joint orientation.

4.1.2.6 Loading

The best strength of a connection are expecting when the loading direction fits well with the direction of maximum strength. In reality and in the construction it is really hard to achieve this kind of situation. In 1996 the study about effect of loading direction was conducted by Prabhakaran. The results of that research were stated in the previous part in the fiber orientation.

In the normal condition, normal loading rate does not affect the strength of mechanical joints in FRP ,however, the FRP material are in essence viscoelastic materials and in the constant loading condition lower strength is excepted. The studies which were done by Schitz in 1996 and also Mosallam in 1999 reported the decrease up to 46% after 420 hours in strength.

The fast rate loading or impact loading is not studied a lot for FRP connection, besides the reliable information is not available now. However, similar to creep, it is expected that impact loading will contribute to a reduction of bolted composite joint strength (Mosallam, A. S., & Knovel 2011).

4.1.2.7 Washer

In the all kind bolted connection washer is reported as an essential part that has a role in generating and sustaining the integrity of bolted connection. The rule of the washer in mechanical connections can be change due to kinds of loading. For instance, when a connection is designed in order to transform the shear, washer can has two substantial rules. It prevents the damage to the bearing surface and also holds up the bolt from embedment. In the case that a clamping force is in purpose the washer also is quite important element in a connection. In this case the washer prevents the surface damage near to the fastener, hold up the bolt from head embedment, hold the hole geometry and finally maintains the tension in the connection. By using a washer torque force will be transferred to the specimen in the form of lateral pressure. In the FRP connection like other laminated washer prevents the composite from splitting through the thickness on the hole loaded side.

By using a washer delimitation area will be spread to a larger area even outside of the washer boundary under compression. The mechanism of the washer rule is simple but useful. If the laminate is strained laterally the part of the laminate under the washer develop shear cracks but is not allowed to expand under compression, thus the lateral expansion, hence, the delamination is spread into a wider area outside the washer boundary (Mosallam, A. S., & Knovel 2011).

Using the washer cannot change the form of failure in the connection. However, the size and also the thickness of washer is important on the fatigue life of a mechanical bolted connection.

The EUROCOMP design code in the design requirement of bolted connection (part 5.2.2.3) has given several recommendations and obligations about the washer in the FRP bolted connection. For instance, the thickness of the washer shall be sufficient to provide even surface pressure on the outer laminate. The thickness of washer should be not less than 20% of the thickness of the outermost laminate through which the fastener passes. (EUROCOMP).

The washer external diameter is quite important parameter in bolt pulling through failure mode. The least external diameter for FRP mechanical connection was suggested as last twice as bolt thickness in FRP design recommendation like CNR recommendation. The oversized washer is not expected to have lots of effects. Report from experimental study which was done by Klett indicated that using the oversize washer can increases static strength approximately 10% (Mosallam, A. S., & Knovel 2011) .

As was mentioned earlier the Washer is quite important in fatigue behaviour and fatigue life also. Hence, the rule of washer in fatigue will be discussed more in detail in the fatigue chapter.

4.1.2.8 Environmental effects

The mechanical properties of FRP material and FRP connection can be degraded under environmental condition especially under the harsh environmental condition. Between large number of scientific researches which were done in environmental effects in composite materials only a few number of them where specifically have been done on connections and specially bolted connections. One of the primary studies which was done in 1976 by Kim and Whitney reported that 40% of ultimate strength is decreasing on the effect of temperature and moisture. That report also reported that temperature has more influences than moisture on bearing strength. That research was one of the best researches on this subject and also mentioned that the combination of temperature and moisture will be 10% more effective in compare to temperature effect only and can be more destructive.

4.1.2.9 Bolt fit

One of the other determinant parameters in the FRP connection is the bolt fit or on the other word hole clearance. In practice the best connection strength is expected when hole is fitted well with the bolt. The allowing clearance for the hole and the washer can reduce the joint bearing strength by up to 25% over that for a complete fit (Mosallam, A. S., & Knovel 2011).

4.1.2.10 Bolt torque

By doing clamping on the bolt failure strength of the connection will be increased by preventing delimitation, however, the bolt in FRP material should not be over tightened. If it happens, it causes the damage to the composite laminated by pressing the washer to the material.

Doyle in 1991 reported that the an increase of up to 31% in the PFRP bolted joint strength is achieving by the tightening the steel bolts by the maximum permissible tension .The applied load axial forces can be calculated from the following expression (Mosallam, A. S., & Knovel 2011) .

$$W_f = \frac{12 * T_s}{r.\tan(\alpha + \theta_s)} \tag{4.12}$$

W_f=Applied axial force, Ib(N)

Ts=applied torque, ft-Ib(N.m)

r=radius of bolt bet area, in. (mm)

α=angle of inclination of bolt threads

θ=angle of static friction

4.1.3 Creep and relaxation in the mechanical connection

Mechanical connections in FRP composites are prone to relaxation or/and creep like many different materials in construction, however the creep and relaxation in FRP is severe than conventional material like steel.

The relaxation in the mechanical connections is a great concern in design and causes loss or reloading the bolted connections especially in pre stressed bolts, for instance, it was reported that for steel bolts (A325 AND A354 grade bolts) immediately after completion of the torqueing, a drop of 2% to 11% of the load had occurred (Mosallam, A. S., & Knovel 2011) .The information and researches about creep are limited and further investigation is needed in this subject. One of the proper researches which was done is this field was conducted by Mosallam and Schmitz (1996) .From that research the degradation up to 46% was reported in 420 hour test in the room temperature condition. The FRP material in essence has time dependent or viscoelastic behavior that manifests itself in creep, stress relaxation and dependence of strain stress diagram on the rate of loading (Kaw A.K2005).

The creep in FRP will be mainly due to creep of the matrix and time dependent growth of fiber matrix deboning and resin micro cracking (Zoghi 2013). The relaxation initiates from high stress level in the threaded part in a connection. Because of that, design guide for FRP connection recommends to use the special type of epoxy for both bolts and nuts in order to decrease the relaxation effects. The material in the connector and the surface condition of the connector is quite important in relaxation. For instance, galvanized bolted which is recommended is harsh and corrosive environment has the double creep and relaxation as stainless steel bolted connection. The reason of this difference is coming from large creep on the zinc coat around the bolt.

The Creep behavior of FRP material can be checked in two different levels based on level of loading. First, at the initial level of loading the creep effect is small and is recoverable, whereas in the higher level of loading the internal damages and deboning is irreversible and will cause permanent deformation. The EUROCOMP handbook like the other references has divided the creep effect and has explained the creep in the three stages as

- Stage one, in the initial stage on loading and when the strain is less than 0.2%.In this stage the creep is recoverable by reloading however some shake down effects should be recognized.
- Stage two, the next stage is constant but not fast growth of creep. In this phase because of finite damage take place the creep behavior is linear and can be partly recoverable.
- Stage three, this stage is the final stage and causes the failure. In the high loading rate stage two may not occur and instead stage three is expected immediately after stage one.

Most creep is expected in the glass and epoxy material whereas the least is related to carbon fibers. Time dependency of different kind of composites is shown in the figures 17. It should be noted that the first diagram (stress versus time) is showing more the relaxation effect and the second diagram (strain versus time) is showing more the creep effects. However, both creep and relaxation are close to each other and can be explain by the same mechanism (Vasiliev and Morozov 2001).

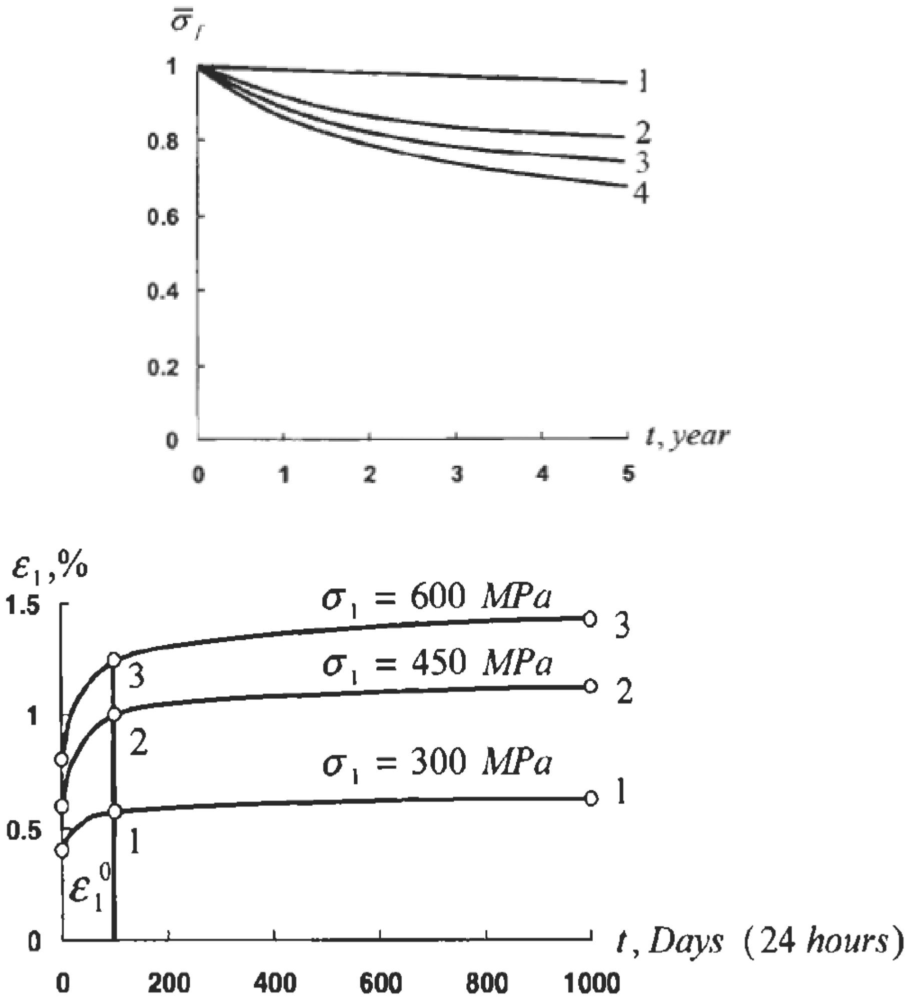


Figure 17 Creep and Relaxation in FRP material, (1) Carbon (2) aramid (3) glass (4) epoxy composites, Vasiliev and Morozov(2001).

Time dependency and also nonlinear behavior of composites under time can be clearer under the diagram which is named as isochoric stress strain diagram.

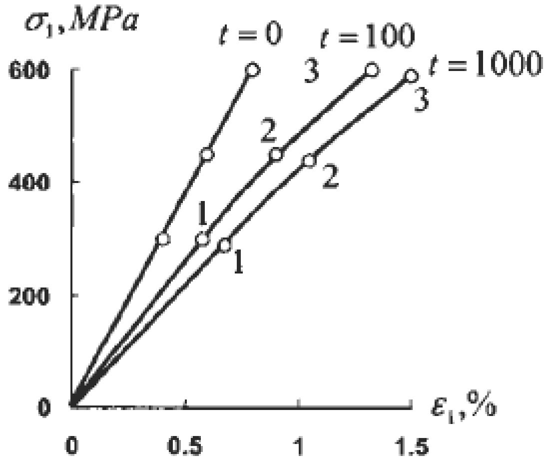


Figure 18 Isochoric stress strain diagram, Vasiliev and Morozov(2001).

4.1.3.1 Effective parameter in creep

Three main parameter as stress, temperature and moisture have more influence on FRP structure and FRP connections. As it was shown in the figure above (strain versus time figure 16 second part) creep is completely dependent to stress level and it was mentioned the level of the loading can omit the intermediate stage of creep.

4.1.3.2 Relaxation of bolted connection

Relaxation on the bolted mechanical connection is quite important parameter; hence it can determine the rigidity of a connection after a loading. If the effect of relaxation is ignored in the designing process it can have harmful consequence in stability and workability of a connection, for instance after relaxation a presumed rigid connection can be changed to a hinge connection. In 1997 the study which was done by Prabhakaran on steel bolted in pultruded composite joints has suggested the following equation for bolt relaxation.

$$P = P_0 T^{-B} \qquad (4-13)$$

Where

P = load at time t, (kN)

P_0=Initial load, (kN)

B = relaxation exponent constant

4.2 Bonded connections

In the introduction for different connection types, the advantages and disadvantages of using bonded connection was explained. In the following, more parameters and characterization related to bonded connection will be discussed in details.

The Bonded connections in civil engineering application are not practical a lot. The technic for joining the elements by adhesive require time, warming condition and clamping or sometimes autoclave condition. That is why using these kind of connection is rare and also difficult in civil infrastructures. In total, in order to reach a proper bonded connection the different parameters like selecting the proper adhesive, surface treatment, adhesive kind, adhesive thickness, proper condition for clamping and fitting the adhesive with adherent should be under consideration.

Mostly a proper bonded connection is known as a connection that can be fulfils the following conditions

- The failure of joint should occur either in the adhesive or in its adherents but not in the interfaces.
- Allowable shear stress and peeling stress of are not exceeded than the limit.
- Allowable through thickness tensile stress and out of plane shear stress should not be exceeded (Zoghi 2013).

The Adhesive joints can be effective in the condition that large surface are available and the members are thin. The Load transferring mechanism in the bonded connection complies with the nature of laminated material as transferring the load as inter laminar shear forces.

The adhesive connections are mostly known between designers as connections with brittle behavior and brittle failure. Usually but not always adhesive connection has brittle behavior and this believe between designers is correct. Most of the time brittle adhesive that causes brittle failure has priority than ductile adhesive which are susceptible to creep. Several parameters have effect on the ductility and brittleness of a bonded connection. The parameters in adhesive and adherent like shear modulus and strength, maximum shear strength, tensile modulus and strength are effective parameter and important parameters in the bonded connections and should be under consideration.

It should be noted that in the following the co-curing technique for bonded connection will not be discuss since, this method is very difficult to be used and to be performed in infrastructural applications.

4.2.1 Adhesive

In the bonded connections adhesive has a substantial rule. Adhesion is associated with intermolecular forces acting across an interface and involves a consideration of surface energies and interfacial tensions (Mosallam, A. S., & Knovel 2011).

Adhesive are categorizing based on different parameters like chemical properties, curing process activation time , curing process requirement and also form of them. In general it is recommended to use more ductile adhesive than brittle one especially when the material has the same stiffness. The most common adhesives that are used widely can be named as epoxies, polyurethanes, cyanoacrylates, methacrylate and also solvent cements. (EUROCOMP& Mosallam, A. S., & Knovel 2011).

Epoxies are the most commonly employed adhesive for joining rigid structural composites (Mosallam, A. S., & Knovel 2011) .Epoxies provide strong joints and their excellent creep properties make them particularly suitable for structural application, but unmodified epoxies have only moderate peel and low impact strength. (EUROCOMP handbook).The Design guide of FRP connection named epoxy as the most employed adhesive for getting the rigid structures and also mentioned that it is environmentally resistance (Mosallam, A. S., & Knovel 2011).To the vast benefits of epoxy the corrosion resistance and not or less affecting by water and heat should be also added (Zoghi 2013).

Polyurethanes are the oldest adhesives and first were employed during World War II. (Mosallam, A. S., & Knovel 2011) . Polyurethanes display high resistance to impact load strong resistance to swelling in the wet and humid environments has ability to remain flexible in temperate environment (Mosallam, A. S., & Knovel 2011) .However, the polyurethanes has weak characteristics to be worked as proper adhesive. Unlike the epoxies it does not have proper creep characteristics .Moreover; it is quite temperature dependent as it is not recommended to use it in the temperature more than 66˚ (Mosallam, A. S., & Knovel 2011).

The EUROCOMP hand book defined the polyurethanes as durable, load bearing adhesives, with adequate water resistance and high tolerant to oil and fluid. Typical service temperatures range for this kind of adhesive was defined from -75 to +80. (EUROCOMP).

Cyanoacrylates are the other kind of popular adhesive in structural application but the application of them is less than the other form of adhesives in civil engineering applications. The Cyanoacrylates adherent can be used with different adherent. The bond strength of the material is quite high and because of that in some commercial paper is named it as super glue. The Super glue is most of the time watery and clear with low viscosity. Against the advantages of the connection which made by cyanoacrylates, the bonded connection by cyanoacrylates are brittle and it is more sensitive to heat and moisture and ultraviolet wave. In the rough and improper surfaces using cyanoacrylates may result of inadequate coverage because of the low viscosity of glue (Mosallam, A. S., & Knovel 2011).

One of three kinds of adhesives which is recently has been in use in structural applications is methacrylate's. These methacrylate's offer some distinct advantages over the other types of adhesives, including the significant improvement in strength and toughness, fast cure rates and ability to bond to wide variety of adherents (Mosallam, A. S., & Knovel 2011) .Tables 13 and 14 which were extracted from EUROCOMP are showing more in details the advantages and limitation of each of adhesive and show some characterizations of several common adhesives.

Table 13 Typical properties of common structural adhesives. EUROCOMP

Property	Epoxy	Phenolic	Polyurethane	Acrylic
Service temperature range ,˚C	-55 to 120	-55 to 90	-155 to 80	-70 to 120
Impact resistance	Poor	Fair	Excellent	Good
Tensile shear	15	15	15	26

strength ,N/mm^2				
T-peel strength ,N/m	< 525	2500	14,000	5250
Creep resistance	Excellent	Excellent	Poor	Poor
Heat cure or mixing required	Yes	Yes	Yes	No
Solvent resistance	Excellent	Excellent	Good	Good
Moisture resistance	Excellent	Excellent	Fair	Good
Gap lamination, mm	None	None	None	0.75
Odour	Mild	Mild	Mild	Strong
Toxicity	Moderate	Moderate	Moderate	Moderate
Flammability	Low	High(liquid),Low(film)	Low	High

Table 14 Advantages and limitation of common adhesive in structural application. EUROCOMP

Epoxy	Phenolic	Polyurethane	Acrylic
Advantages			
High strength	High strength	Varying curing times	Good flexibility
Good solvent resistance	Good hot water	Tough	Good peel
Good gap filling capacities	Good weathering resistance	Good flexibility at low temperature	Good shear strength
Good elevated temperature resistance	Good elevated temperature resistance	Cure at RT or at elevated temperature	Bonding the oil dirty surfaces is possible
Relatively low cost	Relatively low cost	Moderate cost	Moderate cost Room temperature cure
Limitations			
Exothermic reaction	High-pressure	Both uncured and cured are	Low hot-temperature

		moisture sensitive	strength
Exact proportion needed for optimum properties	High temperature cure	Both uncured and cured are moisture sensitive	Low hot-temperature strength
Two-component formulations require exact measuring	Two-component formulation	Poor elevated temperature resistance	Toxic
One-component formulation often require refrigerated storage and elevate temperature cure		May revert with heat and moisture	Flammable
Short pot life	Limited shelf life	Dispensing requirement needed	Odour

The EUROCOMP has defined shear modulus, shear strength, shear strain, tensile modulus and tensile strength as the most important mechanical properties of adhesives which should be under-consideration for design. Material properties of adhesive is quite different base on manufacturer, hence it was recommended that get the mechanical properties of adhesive from manufacturer or from standard testing.

4.2.2 Bonding mechanism

Adhesive bonding occurs as a result of three type of interaction between the adhesive and adherent at their interface (Agarwal and Broutman 2006). Three kinds of bonding as chemical bonding, mechanically interlocking and secondary or electrostatic bonding are known as the forms of bonding. In the chemical bonding the adherent and adhesive will be chemically connected to each other after the chemical mechanism and reaction. This kind of mechanism is known as the most effective form of connection between adherent and adhesive (Mosllam,A.S 2011).The mechanical interlocking is taking place when the adhesive fill into micro pores of adherent. It is enhanced by surface roughness and provides a micro mechanism to mechanically inhibit separation of adherent and adhesive (Agarwal and Broutman 2006). The electrostatic force between adhesive and adherent is the mechanism for secondary bonding. These forces resist shear deformation at the interface and thus provide some shear strength to the bonded line (Agarwal and Broutman 2006).

4.2.3 Surface pre-treatment

The surface pre-treatment is considered as a quite important in the bonding process. The need for careful attention to remove the dirt's and other contamination like chemical, wax, grease is quite essential in the bonded process and inadequate surface pre-treatment is the main causes of the bonded joint failure (Taib et al.2006).In the surface treatment it is recommended to remove both contamination and the weak layer from the surface. And it is expected that the pre-treatment provides surface conditions that can be more readily bonded (Mosallam, A. S., & Knovel 2011).

The proper surface treatment in the FRP material can be achieved by help of the minor abrasion or solvent cleaning. However, the pretreatment of composites are typically more complicated that those employed for the boning of material such as wood, metal or concrete (Mosallam, A. S., & Knovel 2011). For instance, any abrasion by help of sandpaper should be followed by proper solvent wash like alcoholic solvents.

4.2.4 Failure modes

Researches on bonded strength and also failure mode of bonded connection has been started a quite long time ago and the first useful try was conducted by Volkerson in 1938.The efforts in researches has focused on more probable failure modes.

Failure modes can be take place in three main forms as

- adhesive failure
- cohesive failure of adhesive
- cohesive failure of adherent

The Adhesive failure will take place when the martial are mismatched and surface is not treated enough. The Cohesive failure is probable when loads exceeding the adhesive failure and the cohesive failure occurs when the adherent fails due to loads in excess of the adherent strength.

From the mechanically point of view, the more common failure modes in the bonded connection are tension failure, cleavage and peel failure. Hence, between the five probable kinds of failure the shear failure and also compression failure are not too common. One of the best references in this case was prepared by Smith-Hart in 1987.They summarized the adhesive bonded joints failure as following.

- The strongest joints do not fail in the adhesive at all. Rather they fail outside the joint area and at 100% of adherent tensile strength.
- The next highest strength is limited by shear strength of adhesive. The strength of joint is here proportional to the square root of the laminated thickness.
- The weaker failure mode is associated with failure of the adhesive under peel stresses. The peel strength is proportional to the quarter power to laminate thickness.
- Failure in interface between adhesive and adherent is possible.(Hart-

Smith,1987)

Design guide for FRP connection suggested that adhesive bonded connection should be designed as adhesive layer are primarily stressed in shear or in compression. In order to prevent the failure in the a bounded connections the EUROCOMP design code states that any bonded joint should satisfy the following condition as

- allowable shear stress of adhesive is not exceeded
- allowable tensile(peel) stress of the adhesive is not exceeded
- allowable through-thickness tensile stress of the adherent not exceeded
- Moreover, the code states that the allowable in-plane shear stress of the adherent should not be exceeded.

Figures 19 which has extracted from the EUROCOMP are showing the different kinds of failure in the bonded connection.

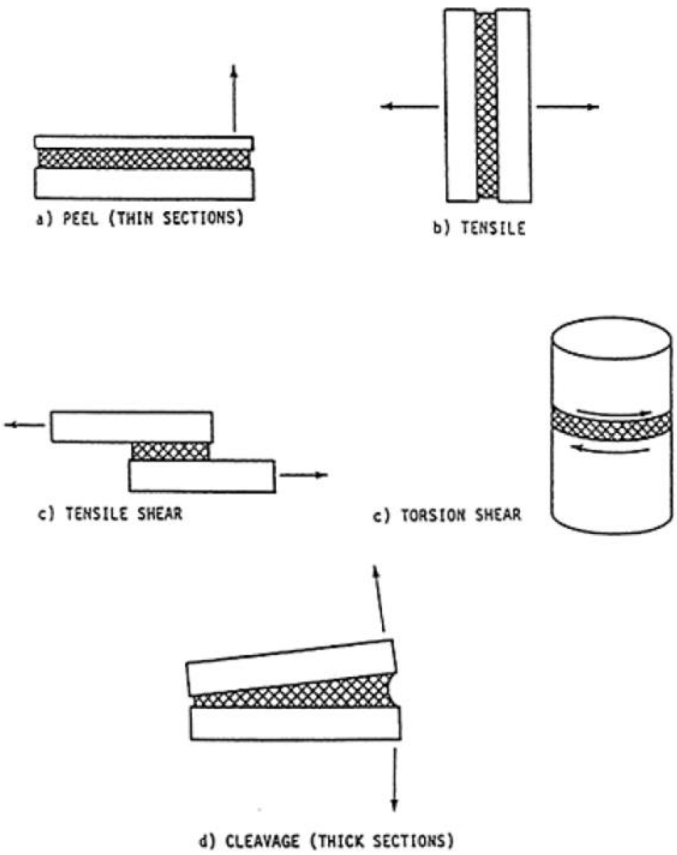


Figure 19 Different kinds of failure in bonded connection, EUROCOMP.

The figure 20 from the same source is showing the possible places of failures in bonded connections.

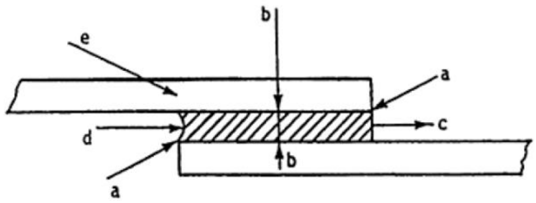


Figure 20 Places for different failures, EUROCOMP.

Like the other form of connections the joint should be designed to ensure that the adherents fail before the bond failure. In the bonded connection it is recommended by Hart and Smith to use adhesive thickness from 0.125 to 0.39 mm. In the bonded connections joint are affecting a lot by unequal adherent stiffness. Hence, in the designing process it is recommended to choose the stiffness of joint as much as possible equal. Regardless of the shape of connection and other parameter which was mentioned before using the adhesive fillet and tapering the ends are effective parameters in the joint efficiency and will decrease the stress concentration at the end of the overlap.

4.2.5 Bonded joint configuration

Joint configuration and the adherent thickness are effective parameter in connection efficiency. Bonded connections can be categorized to the different kinds as following

- single lap bonded joint
- single strap joint
- double lab bonded joint
- double strap joint
- stepped lap joint
- scarf joint

Figure 21 shows the different joint based on joint configuration

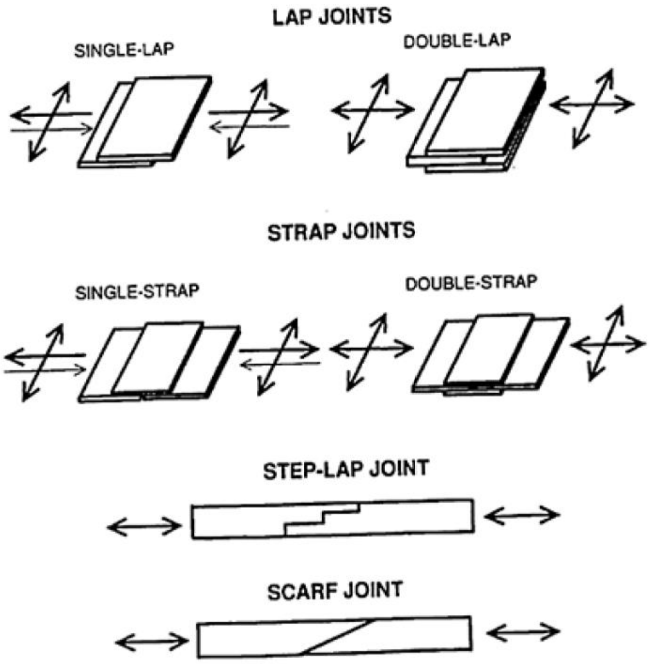


Figure 21 Bonded joint configuration, EUROCOMP.

In the single lap joint when there is not a support for the connection the efficiency of the connection is low because of the eccentricity in the load path. This configuration is the weakest one between the different joint configurations. Moreover this kind of connection is mostly recognized as unstructured connections. In this connections failure in the peel form is more common than other form of failure. This shape is suitable for quality control testing because, it tests simultaneously for a large number effects (Hart-Smith 1974)&(Mosallam, A. S., & Knovel 2011) .Using the thicker adhesive cannot affect the efficiency of the connection and the efficiency will drops rapidly by using the thicker adherent (Mosallam, A. S., & Knovel 2011).

Single strap joint is working like supported single lap joint shape. Single strap joint needs a proper support to work properly. Double lap and double strap bonded joints are the simplest bonded joints and they are efficient in joining thin and moderately thick adherents (Mosallam, A. S., & Knovel 2011).Balance double strap joint and balance double lap joints fitted well for thin and middle thick adherent. In the balance form and for moderate thick adherent peel stresses is determinative for maximum strength. In the thin adherents peel stress is not as important as shear stress and most of the time shear strength becomes greater than adherent strength.

A scarf-bonded joint is the best possibility between the other reconnections for structural applications. It is working properly for almost all of thickness; however design guide books recommend this kind of connection for thicker adherent. In compare to the other connections this connection is more accurate and also rigid. In the assembling process the fitting requirement can be reduced in some situation by co-curing and also bonding of composite laminates. In relation to this ,the EUROCOMP code mentioned that for laminate thickness below 5 mm the use of scarf and step-lap shall be considered with care since the producing the required shapes on adherent may become complicated.

The figure 22 which is sourced by Hart-Smith research in 1974 and from the Boeing

Company research shows the different joint strength or on the other words the efficiency of each joint in related to thickness of adherent and joint detail.

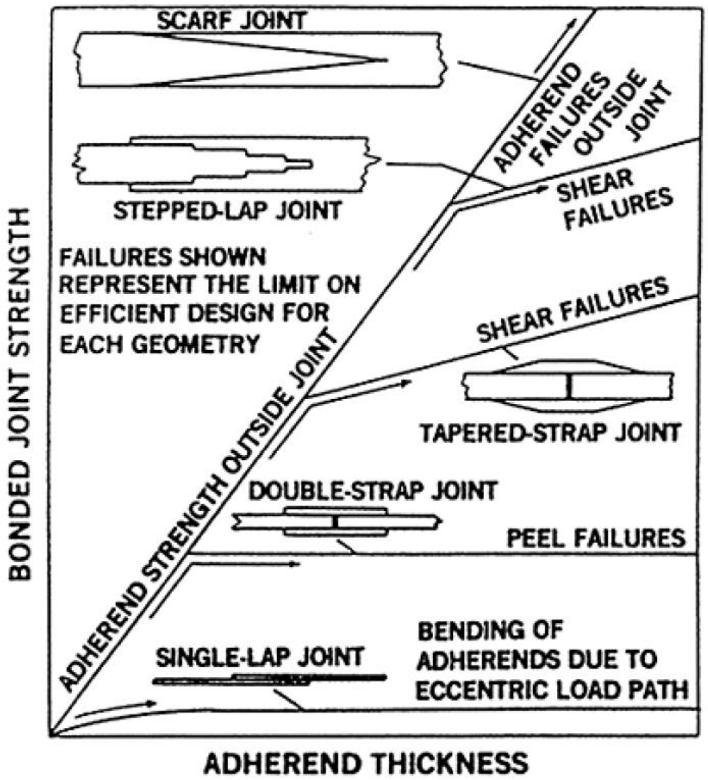


Figure 22 Bonded joint strength, Hart &Smith 1974.

4.2.6 Shear stress of bonded connection

In this part the shear stress calculation for bonded connection is going to present much more in detail

Maximum amount of adhesive shear stress in the bonded connection can be calculated by

$$\tau_{0\,max} = \frac{\lambda P_K \gamma_t}{4}\left[\frac{cosh(\lambda c)}{sinh(\lambda c)} + \Omega \frac{sinh(\lambda c)}{cohs(\lambda c)}\right] \qquad (4-14)$$

Where

$$\lambda = \frac{G_a}{t_a}\left(\frac{1}{E_0 t_0} + \frac{2}{E_1 t_1}\right) \qquad (4-15)$$

And,

P_K, characteristic load per unit width

Ω,The greater of $\frac{(1-\Psi)}{(1+\Psi)}$ or $\frac{(1+\Psi)}{(1-\Psi)}$

And

$$\Psi = \frac{E_1 t_1}{2E_0 t_0} \qquad (4-16)$$

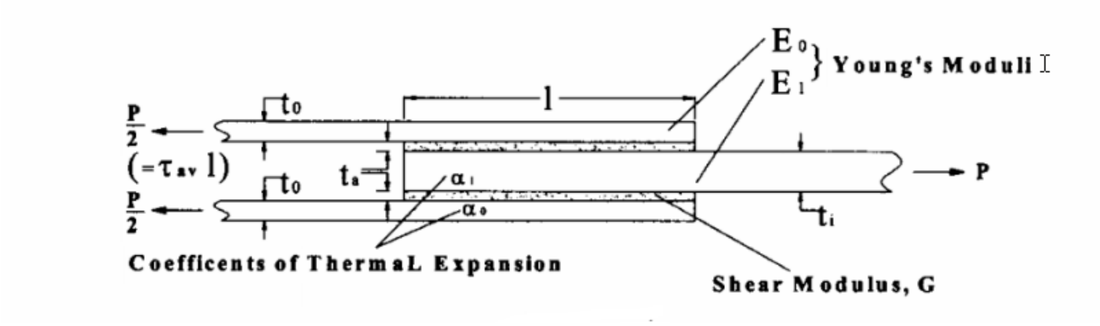


Figure 23 Shear Stress of Bonded Connection.

4.2.7 Peal stress of bonded connection

The formula which is used for calculation of the peel stress for both double lap and double strap bonded joint is given as following (Mosallam, A. S., & Knovel 2011).It should be noted that the possible peal failure is expected to be occurring at the vicinity of the end joints.

$$\frac{\sigma_{c_{max}}}{\tau_p} = \left[3(1-\vartheta^2)\frac{E_C}{E_a}\right]^{\frac{1}{4}} * \left(\frac{t_0}{t_a}\right)^{\frac{1}{4}} \qquad (4-17)$$

Where

$\sigma_{c_{max}}$, Peak adhesive peel stress

τ_p, Peak adhesive shear stress

E_a, Modulus of elasticity of adherent

E_C, Adhesive film tensile modulus in peel

t_0, Adherent thickness

t_a, Adhesive thickness

ϑ, Poisson ratio of adherent

For the single lap bonded joint the with the identical adherent the peak adhesive peel stress can be calculated by

$$\sigma_{cmax} = M_e \sqrt{\frac{E_C}{2t_a D}} \qquad (4-18)$$

Where

D, Bending stiffness of the adherents

M_e, Bending moment in the adherents at the end of the overlap and it is going to be calculated as;

$$M_e = \frac{\frac{P(t+t_a)}{2}}{1+\xi c+\frac{1}{6}\xi^2 c^2} = \frac{kP(t+t_a)}{2} \qquad (4-19)$$

c, half the bonded overlap length in the direction of applied load

ξ ,An exponent descried by the following equation

$$\xi = \sqrt{\frac{P}{D}} \qquad (4-20)$$

In this part of the report only the peel stress in the some important bonded connection has been checked simply. For more information concerning the peel strength of bonded joint the reports from Hart & Smith and Boeing researches in 1981 and 1986 is recommendable.

4.2.8 Design methodology of bonded connection

The EUROCOMP design code and handbook present two main methods for designing of bonded connection as Simplified design procedure and Rigorous design procedure. The simplified design procedure is only recommended for non-structural element and also for designing the elements in the initial stage. This method is based on the test results from standard lap shear test.

The rigorous design procedure utilizes analytical models to determine the stress state in the adhesive (EUROCOMP 2005).This method is based on generally accepted closed-form models and the adhesive behavior in the model is assumed to be linearly elastic.

Based on rigours method in the analysis the joint design is stratified when the following conditions are met (EUROCOMP 2005).

$$\tau_{0max\leq}\tau_{0allowable}$$

$$\sigma_{0max\leq}\sigma_{0,allowable}$$

$$\sigma_{0max\leq}\sigma_{z,allowable}$$

Where

τ_{max} = maximum adhesive shear stress

$\tau_{0\ allowable}$ = allowable adhesive shear stress

$\sigma_{0\ max}$ = allowable adhesive peel (tensile) stress

$\sigma_{0\ allowable}$ = allowable adhesive peel (tensile) stress

$\sigma_{z\ allowable}$ = allowable adherent through-the-thickness tensile stress

4.3 Combined joints

Combined joints are hybrid joint from mechanical fastener and bonded joint with the better strength properties than each of the connection types. The early researches on combined connection which was done by Vinson in1989 stated that the combination of the two connectors can enhance the strength of joint about 50% more than bolted joints only. Some researchers also stated that the combined connection is more effective especially in compare to the bonded joints only.

Using the combined connections has lots of advantages and priority than bolted or bonded connections. Design guide for FRP connection has mention several priority of using the hybrid connection as following

1. Higher overall capacities
2. Greater resistance to environmental and thermal deterioration
3. Less subject to peel or cleavage failures
4. Improved joint stress distribution
5. Increased rigidity
6. Increased fatigue and impact characteristics
7. Reduced peel and cleavage effects in eccentric joints due to presence of mechanical fasteners in combination with structural adhesives
8. Higher safety factor (Mosallam, A. S., & Knovel 2011).

Regardless of the advantages that were mentioned above there are advantages for these kinds of connections in the early construction and assembling and erecting process. Mechanical fasteners can produce the contact pressure required for curing an adhesive. Likewise, adhesive can serve as a means of maintain alignment for mechanical fasteners (Mosallam, A. S., & Knovel 2011).

The EUROCOMP design code does not go in detail to the design parameter of combined connections. The code mentions that in the bonded-bolted joints only the bond or bolts is assumed to carry the joint load. No load sharing between the bond and the bolts is taken into account. Since, a structural adhesive provides a much stiffer load path than the fasteners, the load is carried by the adhesive almost entirely and no load sharing between the adhesive and bolts occurs. (EUROCOMP handbook).In the combined connections the fasteners will be under load only in the case that damage in the connection occurs. In such situation bolt will transfer the load in the not bonded or deboned areas and will be diminish the peak stress in the connections. It is also possible to design a combined connection where service loads are carried by adhesive and ultimate loads by bolts. (EUROCOMP)

Between mechanical connections hybrid connection consisted from FRP and metal can potentially have more advantages that single material when cost, maintenance, weight and structure system performance is considered. (Vincent 2007)(Composite metal bolted joint VAL).

5 Fatigue

Fatigue is quite important issue in the structures especially in the structures under cyclic and fluctuating loads. Mechanical fatigue in composites is progressive and accumulative in nature, as opposed to crack growth behavior observed in the metal. On the other word, in the metallic structure like steel structures observing a crack shows danger of failure and fracture because it grows fast to fracture. Whilst, in the FRP material the crack propagation may be arrested by internal structure of the FRP material and it does not show immediate failure.

Under fatigue loads, composites can experience micro cracking, delamination, fiber fracture, and fiber /matrix deboning. (Zoghi 2013) In the FRP material as well as most of the materials it is expected that by increasing the stiffness the fatigue resistance is also increases.

Unidirectional continuous-fiber reinforce composites are known to possess excellent fatigue resistance in the fiber direction .This is so because the load in a unidirectional composite is carried by the fibers which generally exhibit excellent resistance to fatigue. (D.Agarwal 2006) In the reality the condition is not always like this and FRP materials are in the form of laminates with the different orientation.

Between different FRP composite materials carbon fibers shows the best fatigue resistance against mechanical loads. Moreover, in the CFRP the fatigue life is relatively unaffected by moisture and temperature. (Zoghi 2013) The table 15 shows the degradation of initial strength of different kind of FRP materials per decade of logarithmic fatigue lifetime.

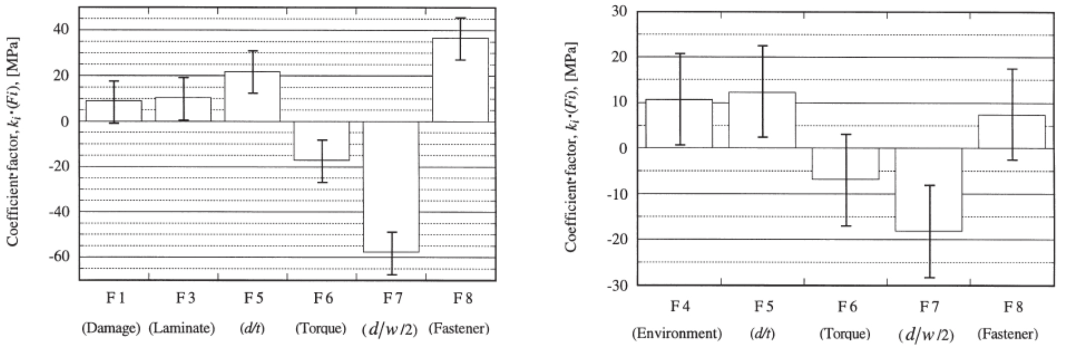
Table 15 Degradation of strength in cyclic loading. Table source: The international Handbook of FRP Composites in Civil Engineering.

FRP material	Degradation of initial static strength per decade of logarithmic fatigue life
CFRP	5%
GFRP	10%
AFRP	5%-6%

5.1 Fatigue in mechanical connection

In this part fatigue criteria more specifically will be discuss in the mechanical connections.

In the mechanical connection it is also expected that internal factors like laminate stacking sequence, fiber and matrix properties, fiber volume fraction, interfacial bonding, hole quality, connection's geometry and fastener type affect the fatigue behavior on FRP connection. Regardless of the material properties and characteristic, loading condition and also the environmental condition like temperature and moisture also were reported as influential parameters in fatigue life of FRP mechanical composite connection. Between all parameters that mentioned above, Persson 1998 has reported the ratio of hole diameter to specimen width, bolt type and the ratio of hole diameter to laminate thickness as most important parameter in fatigue life of mechanical connection (Persson 1998). The graphs in the figure 24 were sourced from his report and show the important parameter under both static and cyclic loading.



Coefficients and confidence intervals from static loading.

Coefficients and confidence intervals from fatigue loading of 1 million cycles.

Figure 24 Important parameter in fatigue life (Persson).

Knowing the internal damage propagation pattern and the development of fatigue damage around the fastener holes in the mechanical connection can be quite hard due the complex behavior of FRP material under cyclic loads. Checking the internal damage mechanism in the material with different fiber orientation shows that the damage mechanism in the bolted connection changes when the fiber orientation changes. For instance, in zero fiber orientation the fiber breakage (Red) takes place because of fiber failure whereas, in 90 degree the matrix cracking (Blue) and fiber matrix shearing (Pink) is the reason for failure, in 45 degree the combination of the fibers and matrix cracking was reported as the reason for failure. The figure shows the illustration of damage propagation predicted for laminated joints at 85% stress level (Danyong 2013).

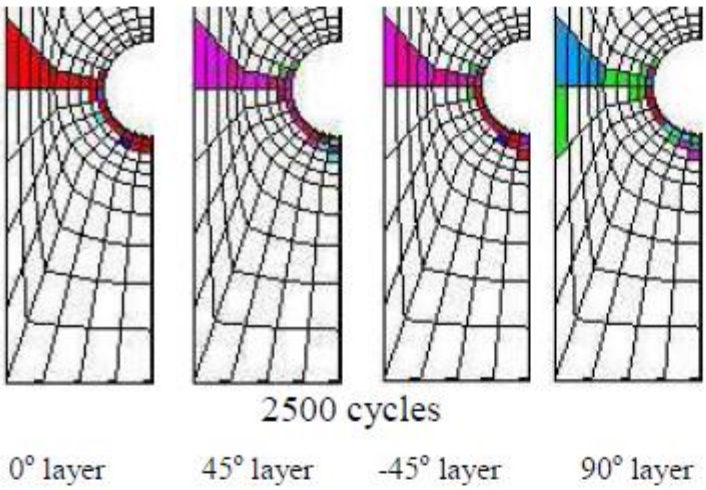


Figure 25 Damage propagation. Figure source: Danyong report 2013.

Damage propagation is quite sensitive to the movement and slip of bolts under the cycling loads. Saunders has explained and mentioned the fatigue damage aspect around the hole in three types as hole wear, damage the laminated near the surface and the nucleation and growth of delamination around the fastener hole

- Hole wear: hole wear can be started by erosion and re-deposition of material and will be lead to the change in the shape of hole. The hole wear in the cyclic loading may causes plastic deformation around fastener hole in both metallic and composite specimens. In this case it is also expected that some elongations occur. This elongation can produces additional secondary bending effect in a connection.
  The figure 26 shows the hole wear in a bolted connection under microscope.

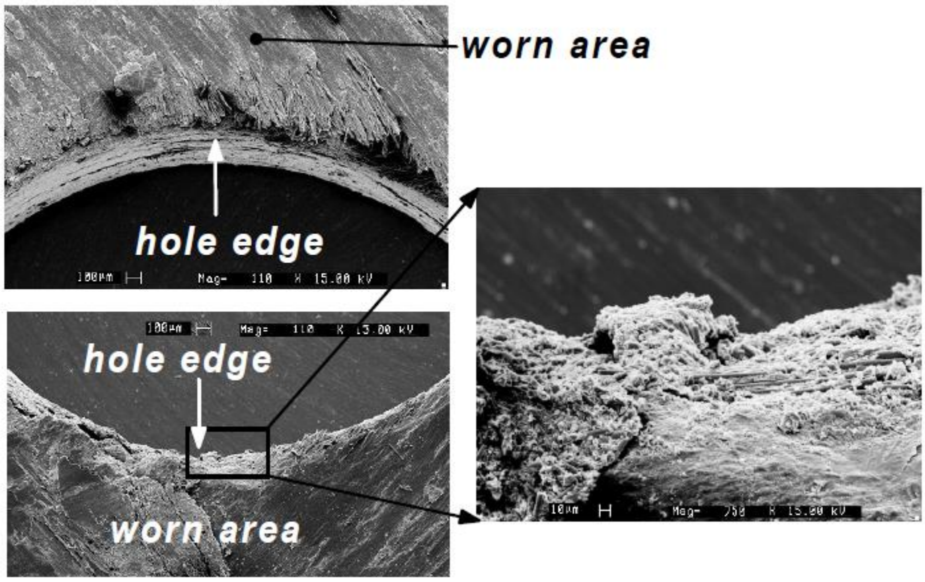
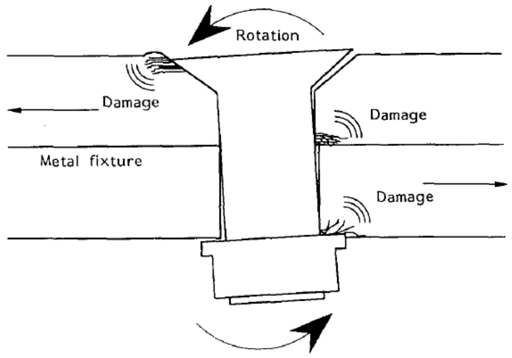


Figure 26 Hole wear in a bolted connection. Figure source: Roman Starikov PhD thesis, KTH University.

- Damage the laminated near the surface: This damage causes the shake and movement of the fastener in the cyclic loading. Under this condition load distribution pattern along the length of fastener will be changes and not remains uniform.
- The nucleation and growth of delamination around the fastener hole: This kind of damage was studied a lot in the researches, but not too much in detail. The growth of delamination is known as one of the major reasons for failure under cyclic loads. Delamination most of the time is starting from drilling the hole and also assembling process and initiating because of loading is quite seldom. The presence of delamination prevents distribution of the load between composites piles, thus lowering the stiffness of the laminated composite. (Starikov 2001)

The figure 27 shows some possible damages which may occur in the bolted connection under the cyclic loads both in schematic and real magnified pictures.



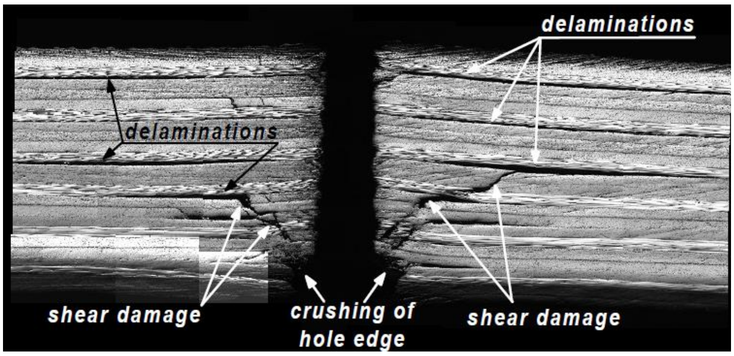


Figure 27 Damage in bolted connections. (Starikov 2001)

As it is obvious the maximum damages are expected for the places with the maximum displacement and maximum loads. In the bolted joints applied loads are transferred via the fasteners and some parts of the applied load is carried by friction forces between the joint elements. When the fasteners are loaded the load distribution along their length is not uniform and this will result in high contract forces localized at the top or bottom hole edges. (Starikov 2001)

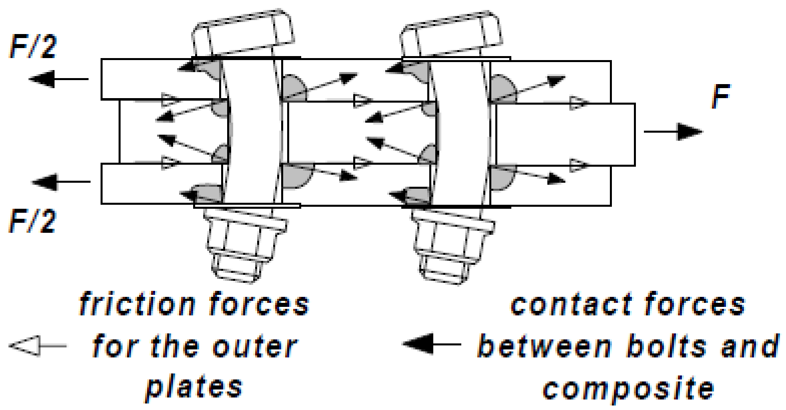


Figure 28 Effect of displacement on mechanical connections. Figure source: (A.M. Van Wingerde 2002).

To clarify the effect of displacement, the displacement on mechanical connection can be compared in the normal or injected bolts. A compression between injected bolted and normal bolted connections shows no improvement on static strength, however the stiffness increases. Whereas the static case, under cyclic load condition major increases of fatigue resistance was reported for injected bolts. (A.M. Van Wingerde 2002).

5.1.1 Tension –tension connection

In total and with few exceptions like where fastener bolts are loose, bolted composites joints have excellent performance under tension-tension fatigue loading condition (Hart-Smith 1996). In the tension-tension loading stress concentration at bolt hole in the FRP mechanical is much higher than the metal joints, although the strength loss under fatigue loading is far less with composites bolted joints as compared the bolted joints. (M.Ayman 2011)

As has mentioned before, geometrically properties of the connection like e/d, w/d and also washer size are known as important parameters in the fatigue behavior of the mechanical connection. A washer in mechanical connection distributes the clamping force gradually to the FRP material and is known as one effective parameter in increasing the fatigue life in tension-tension connections.

One of the researches about the effect of geometry in this loading condition was done by Little and Mallik and the following results was released.

- For highly tightened joints with relatively lower value of w/d (e.g w/d≤4) the fatigue failure is likely to occur away from the bolted joint.
- For highly tightened joints with relatively higher values of w/d (e.g w/d≤6), the likelihood of fatigue failure at the bolted joint increases rapidly.(Little and Mallik 1990)

Design guide for FRP connection has suggested in the tension-tension connections w/d equal to 8 and e/d equals 5 as reasonable and conservative value for design under tension-tension loading. (M.Ayman).

5.1.2 Compression-compression Connection

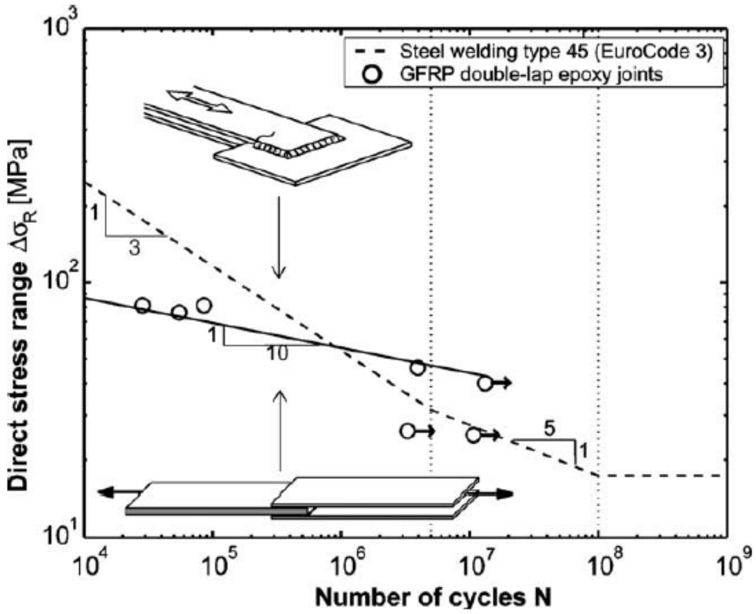
Under compression-compression cyclic loading, un-notched composite laminates can experience delamination particularly after lateral impact damage (Mosallam, A. S., & Knovel 2011).The damage mechanism in this form of loading under cyclic loads is the same as what was mentioned in tension-tension form but with one difference. Unlike tension-tension loading condition the rate of failure after crack initiation grows exponentially.

In this kind of loading the double shear joints is more resistance to fatigue loading than the single shear bolted joints (Mosallam, A. S., & Knovel 2011).Design guide of FRP connection in a rough estimation mentioned that at several million cycles the expected joint strength load as high as 70% of the joint static strength.

5.2 Fatigue in the bonded connection

Like the many other researches related to FRP the researches in the fatigue behaviors of adhesive connection have been done mainly in the areas outside the civil engineering load carrying structures. (Keller 2004).Due to differences between the loading condition and also kind and shape of the elements the results from these researches cannot be used for structural applications. The bonded connection in FRP material especially in GFRP material is more sensitive to fatigue than in the mechanical connections. And in general fatigue life is shorter for tensile loads and longer for compressive loading condition. (Keller 2004).Some researches for instance Thomas Keller researches have shown that fatigue life at one million cycles in the section with bonded connection is between 40% to 80% of the section without any connections, and it is about 25% of static strength. (Keller 2004).

Comparing the behavior of welded steel joints under fatigue with the FRP bonded joints shows that, the FRP connection is more sensitive to small changes in load amplitude.



Comparison of the fatigue live curves of adhesive GFRP profile connections and welded steel connections.

Figure 29 Comparison of the fatigue life. Thomas Keller (2004)

The quasi static behavior of bonded connection under fatigue was reported linear elastic up to brittle failure. It should be also being noted that the failure modes were identical to failure modes of static experiment. (Keller 2004) On the other word, the failure was brittle without any announcement by visible on the specimen surface or deformation. Contradictory to static behavior, under constant amplitude fiber-tear failure mode was reported as dominant failure mechanism. (Keller 2010). Moreover the crack initiation and propagation check out is possible during fatigue life under constant amplitude. It is predicted that the failure mode in the quasi static case is being the same but suddenly. Base on Keller report the fatigue failure of specimens in tension was dominated by cracks in the mats layers of inner laminates. Besides, under compression failure occurred in the roving layer in the middle of inner laminate.

The behaviors of different types of bonded connection are not the same always. For instance, the double-lab joints which were manufactured with GFRP the stiffness degradation was limited to 5-7% for all load level. Besides the stiffness degradation trend was almost linear throughout the entire fatigue life.(Keller 2008) For the step lap joints the situation was different ,since the crack that finally dominated the failure were initiates after an abrupt and uncontrolled failure of the small adhesively–bonded transverse gaps between the composite laminates. (Keller 2008)

5.3 Fatigue in combined connection

The information for fatigue behavior of combined connection is few .However, it is expected the behavior of combined connection under cyclic loading be more like bonded connections. As it was mentioned in the previous chapters, based on available codes like EUROCMP the design of combined connection should be perform base on bonded or mechanical connection and combination of these two connectors is not acceptable. The condition for designing a connection for fatigue load is the same and it is better to consider only bonded effect and not the bolts effect.

6 Experimental test

As it was mentioned earlier one of the objectives in this project was set as, checking the FRP connections experimentally. In order to do that, first of all the mechanical properties of the material was evaluated experimentally. It should be noted this material properties are quite essential for doing the simulation and in order to evaluating the connection behavior. In order to do that and base on the methodology in the first step, four different kinds of tests were performed. In the second step different kinds of connection as bonded, bolted and hybrid connections were checked in the laboratory at Chalmers University. It should be noted that in all performed tests the slip between the jaws of test load cell and the FRP material was big concern and some test results were omitted due to the slip effect. The support gripping force in the all test was set as maximum value.

6.1 Tensile test

The tensile tests with the MTS machine test were performed on the quadric axial Stitched Combo Mats -45/+45 and 0/90 in order to get the tensile chord young modulus (E11), ultimate tensile stress F^{tu} and stress-strain diagram.

In order to perform a standard tensile test on the composite material the test should be performed base on ISO 527-4 or ASTM D3039 standards. Between these two standards ASTM3039 standard for in-plane tensile properties of polymer matrix composites was chosen. The schematic figure for the test set up is shown in the figure 30.

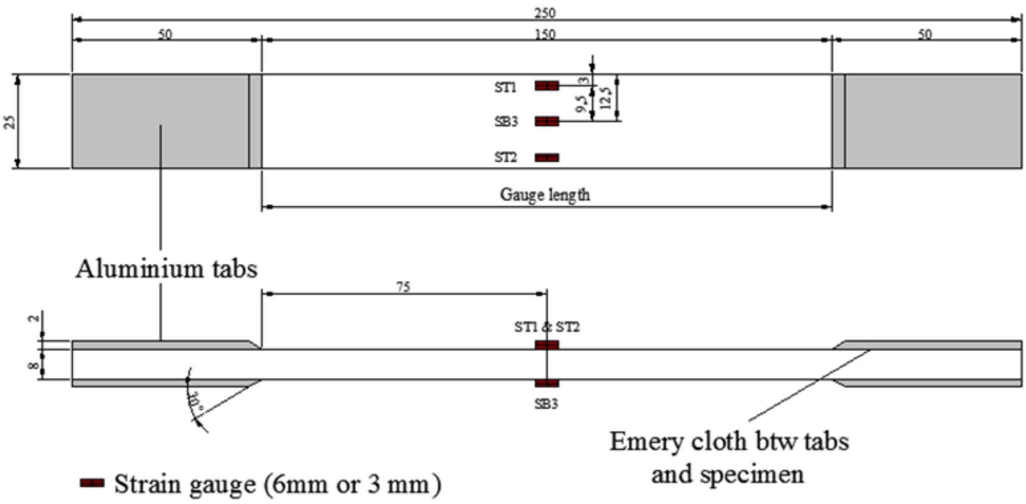


Figure 30 Schematic result for tensile test.

Figure 31 Tension test set up.

6.1.1 Tension test result

The table 16 shows the tests result for four samples which were under tension test.

Table 16 Tension test result.

sample	T3	T4	T5	T6
E1(Gpa)	24,45	23,11	26,175	27,165
F^{tu}(N-mm2)	340,73	343,34	342,19	347,46

The picture 32 shows the test result for the four tests. To be on the safe side and due limited number of test E11 equals to 24,45 Gpa and ultimate tensile stress equals to 340,73 N-mm2 is recommendable for further calculation. It should be noted that all tension failure modes took place in DGM (edge delamination failure mode). See figure 33

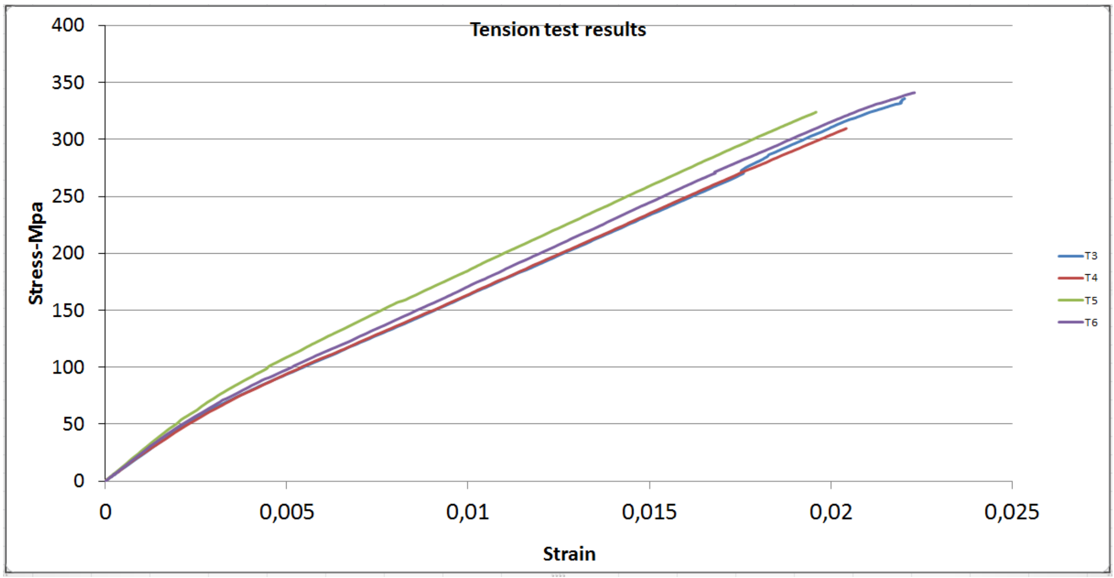


Figure 32 Tension test results.

As it is clear in the graph in the figure 32 the stress-strain curve slope or on the other word, modulus of elasticity has changed after initial loading .Hence, it is also logical to define two slope or modulus of elasticity for tension, one for the initial step as E1 and the second one for the second slope as E2.The table 17 shows the modulus of elasticity for the second part of slope.

Table 17 Tension Modulus of elasticity for the second part.

sample	T3	T4	T5	T6
E2(Gpa)	13,93	14,00	15,368	14,612

The failure was take place in the form of DGM (edge delamination failure mode).The figure 35 shows the failure in the four performed tests.

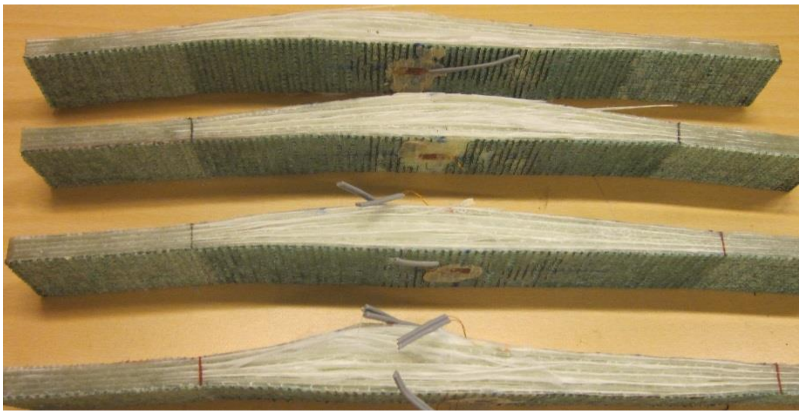


Figure 33 Tension failure in DGM.

6.2 Compressive test

The Compressive tests were performed in order to determine the compressive modulus, compressive strength and ultimate compressive strength of polymer matrix composite materials. The tests were matched with the ASTM D 3410 procedure B criteria. The compressive tests can be performed with ASTM D3410, ASTM D695, and ISO 8515 testing standard (Zoghi 2013). Between these standards the ASTM standard has been chosen for the compressive test performance and evaluation. The figure 34 shows the schematic form of test set up.

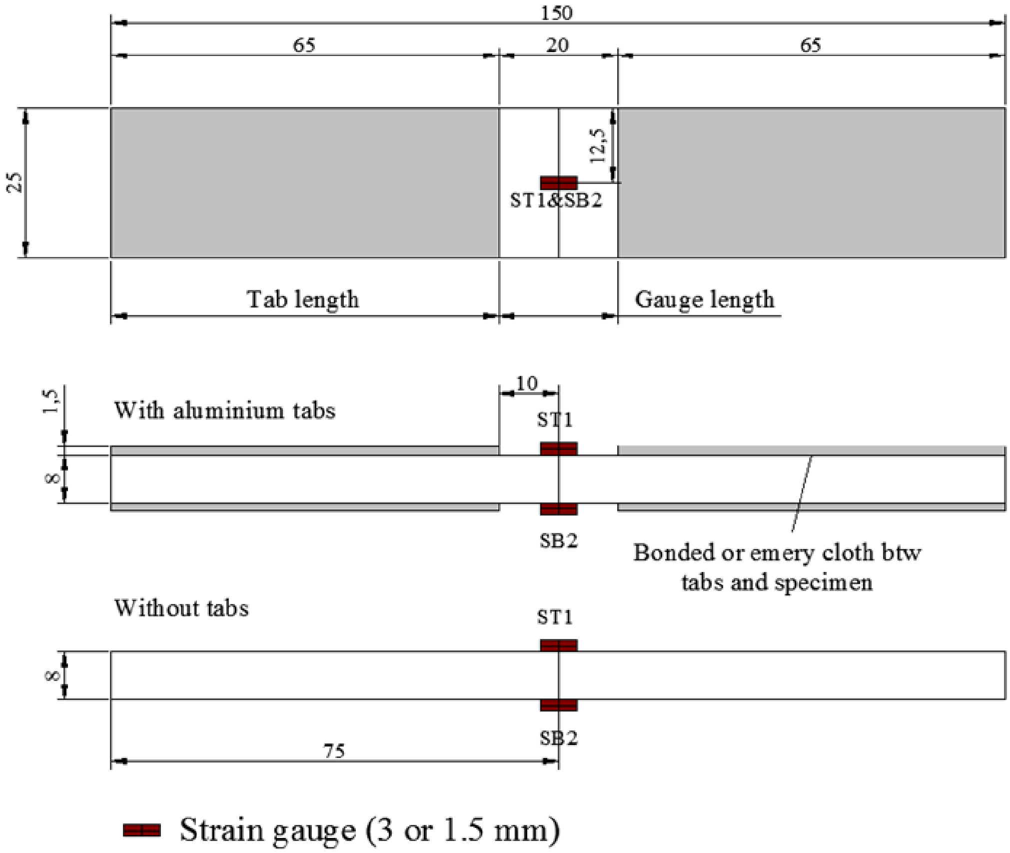


Figure 34 Compressive test schematic shapes.

The figure 35 also the test set up for compressive test.

Figure 35 Compressive test set up.

6.2.1 Compressive test results

The table 18 shows the tests result for four samples which were under compressive tests. It can be evaluated the Modulus of elasticity as 25,43 Gpa and also ultimate compressive strength as 229,05 Mpa for compressive tests..

Table 18 Compressive test results.

sample	C3	C4	C5	C6
E1(Gpa)	25,43	25,79	26,30	26,80
F^{tu}(N-mm2)	229,905	226,84	226,84	240,68

The figure 37 shows the test stress strain graphs for the compressive test.

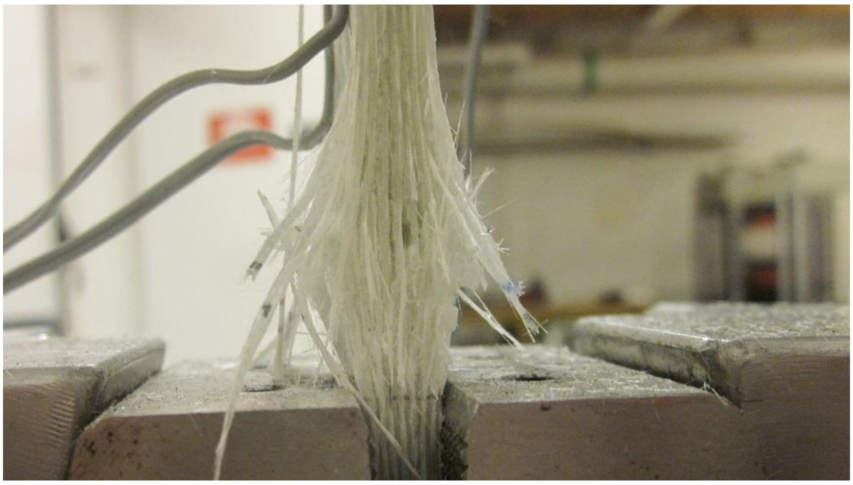


Figure 36 *Compressive test failure.*

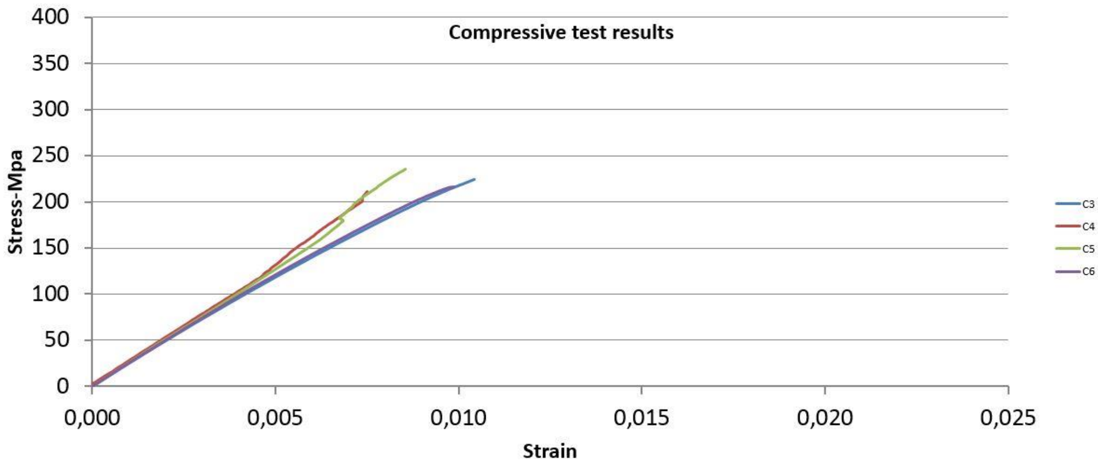


Figure 37 *Compressive test results*

As it is clear the behavior of material under the compressive test is not like tensile test and it is not logical to define the two different Modulus of elasticity. The figures 36 show the failure form in the tests and also test machine set up for compressive test.

6.3 Shear test

The shear test for evaluation of the shear properties of composite was performed based on the ASTM ,D7078/D7078M. The tests have been performed by help of two fixture halves (Figure 38). In the experimental test when loaded in tension using a mechanical testing machine, the fixture introduces shear forces in the specimen that produce failure across the notched specimen (ASTM ,D7078,2014).

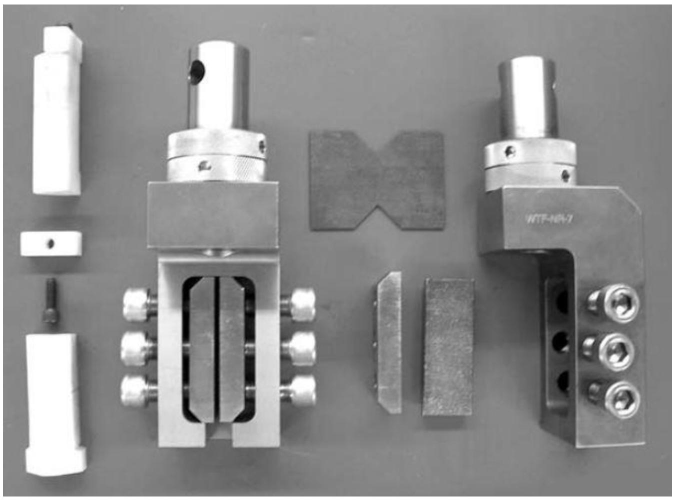


Figure 38   Shear fixture and specimen, ASTM

The figure 39 shows the test machine under the shear testing.

Figure 39   Shear test set up.

6.3.1.1 Shear test results

The table 19 and the graph 40 are showing the tests result for five samples which were under shear tests. As it is clear the behavior of the specimen under shear testing are not completely linear and the two different shear modulus one for the first part and the other for the second part of the graph can evaluating. The first shear modulus has been evaluated for the 1500-2000 με and the second modulus has been calculated for the 5000-8000 με.

The ultimate shear strength of the specimens are not following the same pattern and more tests for the better evaluation in the future is recommended.

Table 19 Shear test result

sample	S1	S2	S3	S4	S6
G_1(Gpa)	7,92	8,86	8,08	8,53	7,95
G_2(Gpa)	6,27	7,21	6,49	6,95	6,43
F^{tu}(N-mm2)	133,06	176,36	183,12	114,12	135,8

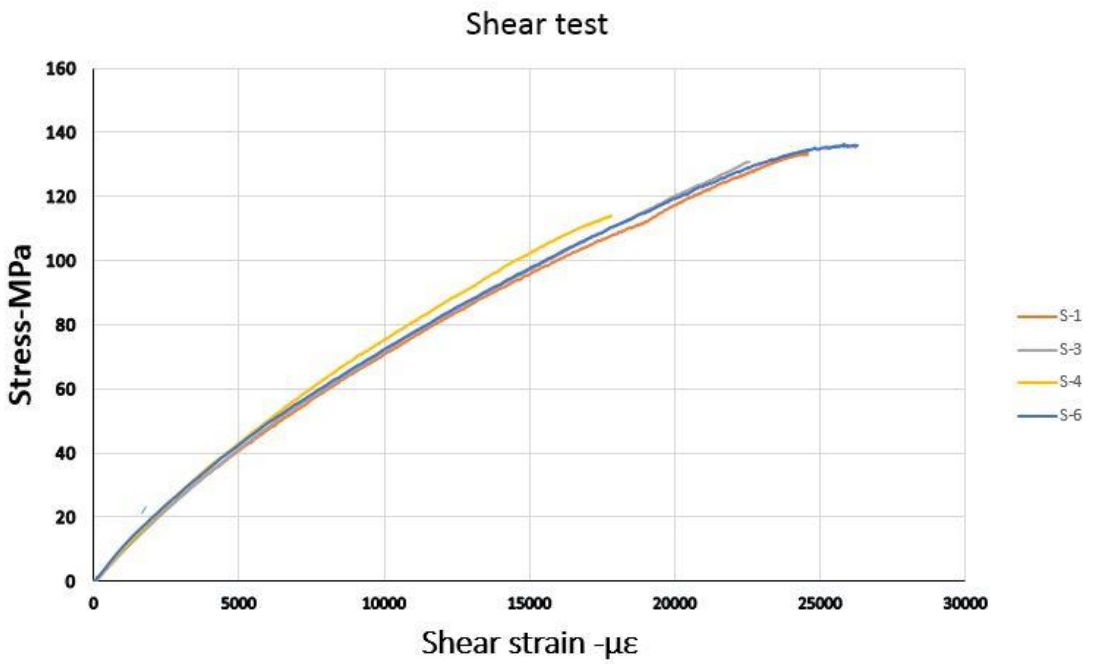


Figure 40 Shear test results.

6.4 Connection test

In order to check the different kinds of connection's behavior different numbers of tests have been performed at Chalmers Laboratory. Tests have been categorized in three main groups as bonded connections, bolted connections (simple bolted connections) and bolted connections with inserts.

The figure 41 is showing the test set up for bonded and bolted connections in schematic view. In should be noted that all test set up have been set based on ASTM Standard.

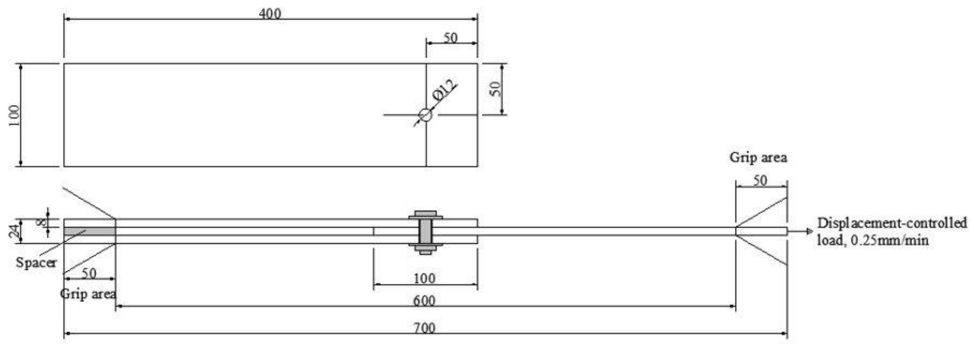
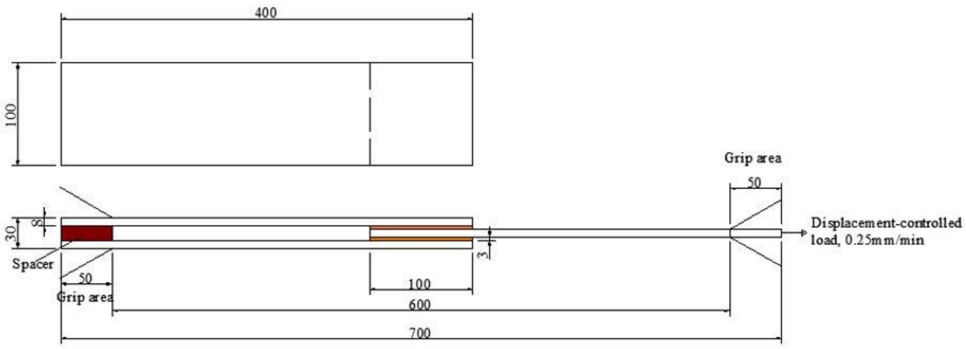


Figure 41   Bolted connection test set up



***Fi**gure 42   Bonded Connection,Test set up.*

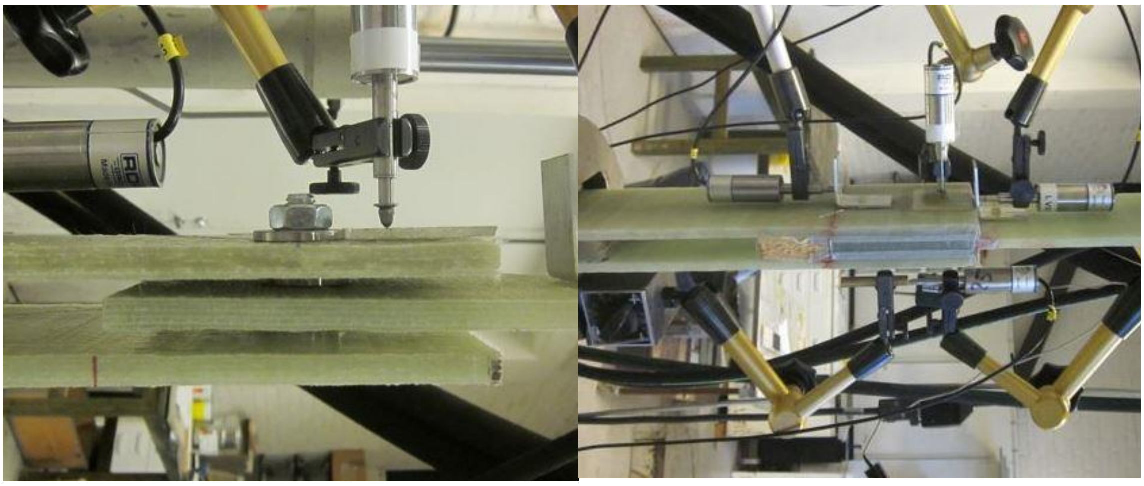


Figure 43   Bonded and Bolted connection.

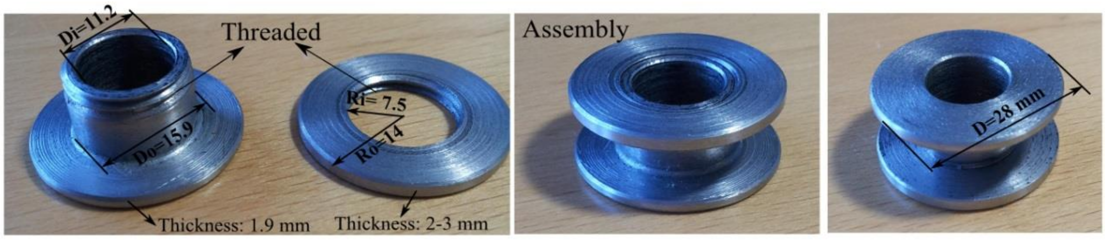


Figure 44 Insert in Mechanical Connections

6.4.1 Connection test results

The graph in the figure 45 is showing different group of connection's test results. In should be noted that each of graphs are coming from different numbers of tests and not only single test.

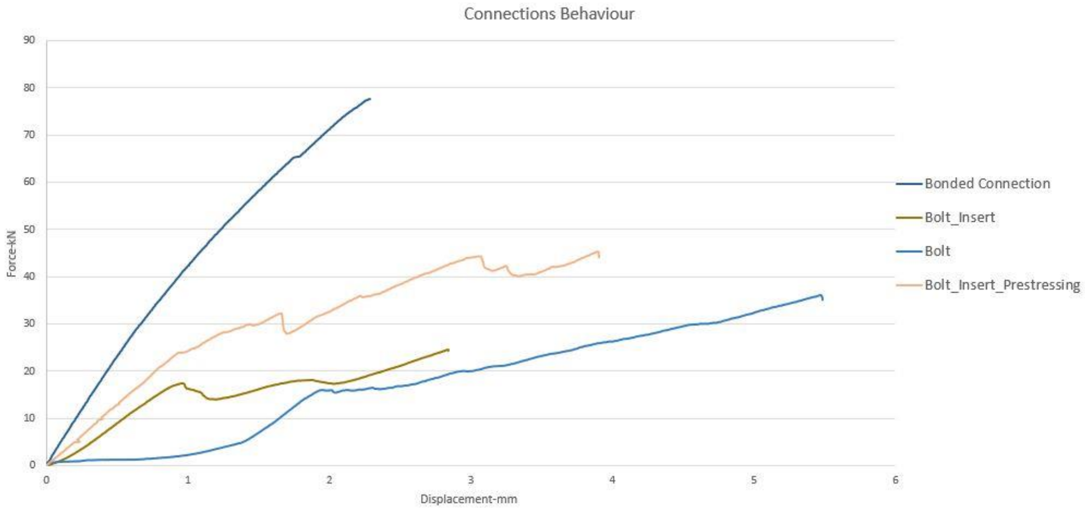


Figure 45 Connection test results

As it was expected the following results have been observed

1- The bonded connection has the most stiffness and less displacement rather than the bolted connections.
2- The slip and initial displacement was considerably low in bonded connections.
3- In normal bolted connections the initial slip is high. In addition to the initial slip the connection stiffness was the least between different kinds of connections.
4- Pre-stressing in the bolted connection can decreases the initial slip but it does not have any effect in connection stiffness.
5- Using the insert can decreases the initial slip and also it can increase the total stiffness.

The behaviour of mechanical connection with insert is between the bolted and bonded connection and is promising in the improvement of connection behaviour and capacity.

7 References

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