CHALMERS
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Single Glued-in-Rod Connections for Timber Structures

A state-of-the-art review

Master's thesis in Structural Engineering

VIKTOR WIBERG

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Department of Architecture and Civil Engineering
Division of Structural Engineering
Steel and Timber Structures
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

Connections with glued-in rods in timber structures are generally seen as a connection method with great potential, especially in times when there is more focus on sustainable materials. The technology is based on rods being glued into pre-drilled holes in timber elements. The mechanical advantages of GiR include reliable strength under regular conditions, high local force transfer, relatively high stiffness and the possibility of ductile behaviour. There have been several research projects that have dealt specifically with glued-in rods, but a final definition of the mechanics and a universal approach for the design of GiR still does not exist. The aim of this master thesis is therefore to present a state-of-the-art overview and evaluate design proposals for GiR connections. This is done in order to contribute to the establishment of a reliable design method for GiR in Eurocode 5.

A literature review was conducted in which possible failure modes and their influencing parameters were identified and reviewed. The dominant failure mode of adhesive bond-line failure was studied since it was identified as the most important failure mode for design of the pull-out strength for GIR connections. The focus was on GiR connections with a single rod, but since the behaviour and mechanism of failure at the adhesive bond-line is similar between single and multiple GiR, conclusions drawn from studies on single GiR can therefore be applied to GiR joints with multiple rods. The actual work consisted of a comparison between selected design equations and experiments and was implemented by first applying the input data from the various experimental studies on the selected design proposals and thereby calculating a theoretical capacity. After that, a ratio between the theoretical capacity and the experimental values were calculated, $F_{k,criteria}/F_{k,test}$. For each design proposal, two scatter plots were made, where the ratio, $F_{k,criteria}/F_{k,test}$, was plotted versus either the anchorage length or the slenderness. A distinction between tests performed on either hardwood or softwood was made to see which of these two timber categories that corresponds best with the design proposals. Two additional plots were then made with linear approximations based on the previous made scatter plots to clarify and simplify the comparison between the design equations. Furthermore, the capacities of the test specimens were also plotted versus anchorage length and slenderness, respectively.

The results were further analysed and discussed. When it comes to estimating the capacity of GiR connections with design equations, it is very important to have a conservative approach, since overestimating the capacity can lead to errors that can have major consequences for the structure. Furthermore, there is an interest in a design equation with broad application on different types of timber. The results showed that the proposals that met these criteria best were the ones from EC5 (2003) and DIN (2008). The equation from DIN (2008) had less scatter and the conclusion is therefore that it is the most reliable design equation of those studied in this work. Nevertheless, DIN (2008) would benefit from being reviewed for increased efficiency.

Keywords: Glued-in Rod, Timber, Adhesive, Design proposal

Förband av inlimmade skruvar i träkonstruktioner

En översikt

Examensarbete för masterprogrammet Structural Engineering and Building Technology

VIKTOR WIBERG

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för Konstruktionsteknik
Stål- och träbyggnad
Chalmers tekniska högskola

Förband med inlimmade skruvar i träkonstruktioner ses generellt som en anslutningsmetod med stor potential, särskilt i tider med fokus på hållbara material. Tekniken bygger på att skruvar limmas in i förborrade hål i träelement. De mekaniska fördelarna med inlimmade skruvar (på engelska Glued-in Rods, GiR) inkluderar tillförlitlig styrka under normala förhållanden, hög lokal kraftöverföring, relativt hög styvhet och möjlighet till segt brott. Det har funnits flera forskningsprojekt som har behandlat inlimmade skruvar, men en slutgiltig definition av mekaniken och ett universellt tillvägagångssätt för dimensionering av GiR saknas fortfarande. Syftet med detta masterprojekt var därför att presentera en överblick och utvärdera designförslag för GiR-anslutningar. Detta görs för att bidra till upprättandet av en tillförlitlig konstruktionsmetod för GiR i Eurocode 5.

En litteraturstudie genomfördes där möjliga brottmoder och deras påverkande parametrar identifierades och granskades. Den dominerande brottmoden, brott vid limmets ”bond-line”, studerades eftersom den identifierades som den viktigaste brottmoden för utformning av GIR-anslutningar baserat på utdragningsstyrkan. Fokus var på GiR-anslutningar med en inlimmad skruv, men eftersom beteende vid limmets ”bond-line” även gäller för anslutningar med flera inlimmade skruvar, kan slutsatser även tillämpas för dem. Arbetet bestod av en jämförelse mellan utvalda dimensioneringsekvationer och experiment, och genomfördes genom att först applicera data från de olika experimentella studierna på de utvalda dimensioneringsförslagen och därmed beräkna en teoretisk kapacitet. Därefter beräknades ett förhållande mellan teoretisk kapacitet och experimentella testvärden, $F_{k,criteria}/F_{k,test}$,. För varje dimensioneringsförslag gjordes sedan två spridningsdiagram, där förhållandet $F_{k,criteria}/F_{k,test}$ plottades mot antingen förankringslängden eller slankheten. En åtskillnad mellan försök utförda på antingen hardwood eller softwood gjordes, för att se vilken av dessa två träkategorier som dimensioneringsförslagen korrelerar bäst med. Två ytterligare diagram gjordes sedan med linjära approximationer baserat på spridningsdiagrammen för att förtydliga och förenkla jämförelsen mellan de olika dimensioneringsekvationerna. Vidare plottades även testvärdenas kapacitet mot förankringslängd och slankhet.

Resultaten analyserades och diskuteras. Det är viktigt att dimensioneringsmetoder resulterar i konservativa kapaciteter för GiR-förband, eftersom en överskattning av kapaciteten kan leda till stora konsekvenser för konstruktionen. Vidare var det av intresse med en ekvation som kan tillämpas på olika virkestyper. Resultaten visade att de förslag som bäst motsvarade dessa kriterier var de från EC5 (2003) och DIN

(2008). Ekvationen från DIN (2008) visade mindre spridning av resultaten och slutsatsen är därför att det är den mest pålitliga designekvationen av de som studerats i detta arbete. Ändå skulle DIN (2008) dra nytta av att bli granskad för ökad effektivitet.

Nyckelord: inlimmade skruvar, trä, lim, designekvationer

Contents

Preface

This master thesis was the final part of the master program Structural Engineering and Building Technology at Chalmers University of Technology. The thesis was carried out at Sweco Structures AB from February 2018 to January 2019.

I want to thank my examiner Karin Lundgren, supervisor Rasoul Atashipour and opponent Stina Åkesson at Chalmers, as well as my supervisor at Sweco, Isak Berneheim, for all their help and support throughout the process.

Stockholm, January 2019

Viktor Wiberg

Notations

Upper case letters

D	diameter of the hole [mm]
L	glued in anchorage length [mm]
$R_{ax,k}$, F_k	characteristic axial resistance [N], [kN]

Lower case letters

d	diameter of the rod [mm]
d_{equ}	equivalent diameter [mm], equal to the smaller of the hole diameter and 1,15d
e	glue-line thickness [mm]
$f_{k1.k}$	characteristic value of the bond line strength [N/mm^2]
$f_{v,\alpha,k}$	characteristic shear strength of the wood at the angle between the rod and the grain direction
k	glue strength parameter
l_a, *L*	glued in anchorage length [mm]
α	the angle between the rod and the grain direction
λ	ratio between anchorage length and diameter of the rod
ρ_k	characteristic density of the timber [kg/m^3]
ω	stiffness ratio of the joint

1 Introduction

Timber is increasingly used as a structural material for buildings since it, compared to steel and concrete, has sustainable benefits as a renewable material that stores carbon dioxide, and structural members can be recycled (Ogrizovic, et al., 2017). Joints are important elements in timber structures since the load bearing capacity and overall stiffness of the structure correlates with the capacity and stiffness of the joints. Furthermore, joints have a big impact on the cost of the structure and can take up to 70% of the design time (Batchelar & Fragiacomo, 2012).

Available connection methods can be divided into three categories: 1. direct contact between timber members, e.g. carpentry type joints; 2. dowel type mechanical fasteners, e.g. bolts, pins or dowels, which is the most common; 3. load transmission by means of adhesive bonding. Glued-in Rod (GiR) connections however, is a combination of category 2 and 3 (Gonzales, et al., 2016), and has the benefits of good resistance against axial, lateral and torsion forces as well as bending moments (Duchon, et al., 2016).

The technique of GiR is based on the strengthening of timber with stiffer materials, e.g. sticking rods made of steel or glass fibre composites. Unlike more traditional connection types, e.g. dowels, the stress distribution of GiR occurs along the bonded length of the rod (Di Maria & Ianakiev, 2015). GiR was introduced in the 1970's and was initially used as reinforcement to prevent cracks in beams of laminated timber subjected to stresses perpendicular to the grain. Since then, GiR joints have reached other fields of timber engineering, e.g. moment-resisting connections in beams, frame corners and column foundations (Steiger, et al., 2015).

Even though GiR joints have practical advantages they are not used as much in practice as they have potential to, according to a survey filled out by scientists, representatives and designers from the timber industry. The reason is, according to the survey, a lack of standards and adequate information on the design (Stepinac, et al., 2013).

Since the beginning of the 1990's extensive research and experimental studies have been conducted on GiR joints and a European project that started 1998, named GIROD, with the main objective to establish design rules, resulted in a new calculation model which was suggested for implementation in the pre-version of the Eurocode 5 as Annex C in Part 2. However, it was discard following a decision from the TC 250 (Källander, 2004), due to different scientific approaches in earlier studies and different approaches to establishing design equations in the different countries (Tlustochowicz, et al., 2010).

There have been several projects since GIROD that have dealt specifically with glued-in rods, but a final definition of the mechanics and a universal approach for designing of GiR still does not exist. Therefore, there is a serious need for a broader-purpose European design procedure.

1.1 Aim and objectives

The aim of this master thesis is to present a state-of-the-art overview and evaluate design proposals for GiR connections. This is done in order to contribute to the establishment of a reliable design method for GiR in Eurocode 5. To fulfil the aim, a set of objectives were defined as follows:

- Getting an overview of possible failure modes, and the parameters that influence the failure modes and mechanical behaviour, through a literature review of existing research
- Identify which failure modes are most relevant for design
- Compile design proposals and experimental results from literature
- Compare theoretical values derived from different design proposals with experimental results to find out which design suggestion best correlate with reality
- Identify which aspects of GiR that need further investigation

1.2 Limitations

The focus of this work has been on GiR as a connectivity solution for timber structures and thus other areas of application are not fully investigated. The study was further limited to GiR connections with a single rod, since it facilitates analysis of isolated parameters and their influence on the mechanical behaviour. Furthermore, the design aspect that were examined was the estimation of the pull-out capacity at axial loading, which means that other design aspects and loading situation, e.g. shear or bending, was not considered. These limitations were chosen because there is still no consensus about the design approach for the pull-out strength despite several studies.

To do a fair comparison, design proposals were limited to ones that estimates the characteristic resistance of a single GiR and comes from European research, and test series to ones that met the following criteria:

- glulam or sawn timber
- threaded rods made of steel that have been inserted parallel or perpendicular
- epoxy type of adhesive
- axially loaded specimens
- moisture content around 12 percent

1.3 Method

A literature study was conducted to get a sufficient theoretical background and an understanding of the characteristics and features of GiR. This was done by studying research reports and other relevant literature. The material was found through searches in online databases and by discussions with experts on the subject.

While doing the literature review, studies that contained experimental research where highlighted and selected as well as studies that contained design proposals. Limitations were then established for the experimental studies to enable the application of design proposals as well as make a correct comparison between design proposals possible. The design proposals were then applied to the experimental research, and ratios between theoretical and experimental values were calculated. Finally, the results were plotted and analysed.

2 Connections with GiR

In this chapter, the basics of GiR joints are presented, which includes the structural and material characteristics, applications, manufacturing process, advantages and disadvantages.

2.1 Included components

The name of the connection, glued-in rod, is self-explanatory. Rods are glued into pre-drilled holes in timber members of beam and pillar systems. GiR is considered a hybrid joint since it consists of three parts; timber, rod and adhesive. An illustration of the connection can be seen in Figure 2.1. Timber is used as the main structural element, and the adhesive transfers the load from the rod to the timber element by its cohesion and by its interfaces (Rossignon & Espion, 2008). The adhesive bond line, which includes the adhesive layer and the interface between adhesive and adherents, is the name of the area where the force from the load is transferred. It affects the overall behaviour of the GiR and is therefore of great interest for design (Steiger, et al., 2015).

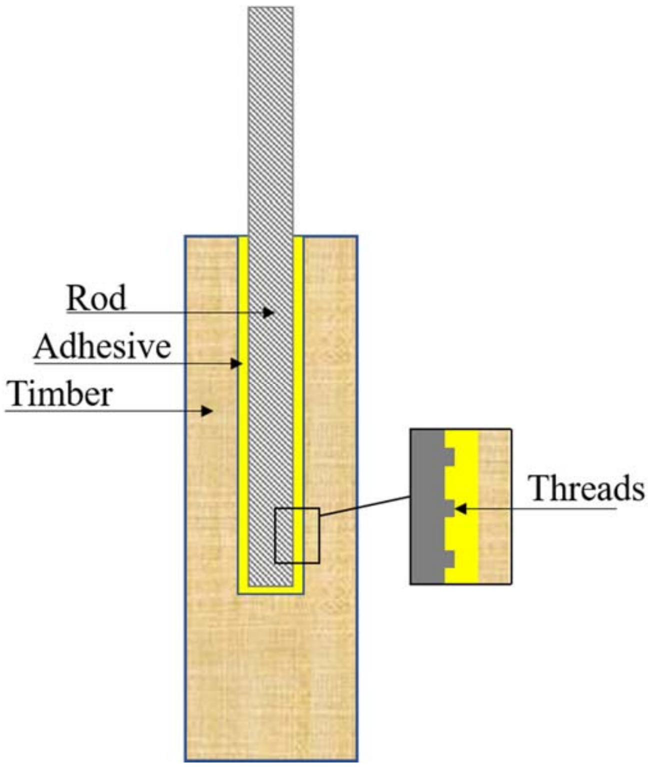

Figure 2.1 Components of GiR. Image reproduced with inspiration from (Feldt & Thelin, 2018).

2.1.1 Timber

The load capacity in bending to the weight ratio for timber is up to three times higher than steel, and as much as ten times higher than reinforced concrete. Other advantages are good insulation ability and relatively low self-weight. Timber is an anisotropic material, which means that it has different mechanical properties in different directions. Generally, timber has good strength and stiffness properties parallel to the grain and is weaker in the other directions (Fueyo, et al., 2010). Furthermore, timber is stronger in tension than in compression and the strength correlates with the density. Timber with higher density usually fails in tension while lower density timber tends to exhibit gross compressive buckling before there are any signs of failure in tension (Alam, et al., 2009).

Timber is also a hydroscopic material, which means that it adapts its moisture content to its environment with swelling and shrinkage as an effect, which affects the mechanical properties. High moisture content can also lead to mould and rot growth, which have negative effect on the mechanical functionality (Alam, et al., 2009).

GiR connections are most suiTable for larger connections, where high load capacity is required, and therefore glulam made of softwood is often used since it is difficult to manufacture sawn wood with desirable dimensions. The insertion of the rods is most commonly done either perpendicular or parallel to the grain direction. Furthermore, it is important that a high quality of the wood can be guaranteed. Therefore, only strength graded timber and glulam whose quality has been checked are used. Other types of engineered timber have been tested e.g. Laminated Veneer Lumber (LVL) which has the advantage according to the studies of (Stepinac, et al., 2016) that there is no significant difference in the pull-out strength for different glue directions of LVL.

2.1.2 Adhesive

The role of the adhesive is to connect and transfer forces between the timber and the rod. Furthermore, the connection should be stiff enough so that there are no deformations other than those created by the timber (Otero Chans, et al., 2010). In addition to strength and stiffness qualities, other characteristics such as viscosity, curing times, porosity requirements of the timber piece and avoiding retraction should be considered for adhesives in GiR connections (Otero Chans, et al., 2010).

The most common used adhesive types for GiR connections are epoxy (EPX) and polyurethane (PUR). A test carried out during the GIROD project examined adhesives that were based on polyurethane (PUR), epoxy (EPX) and phenol resorcinol (PRF) and concluded that even though PRF has the highest pull-out capacity, followed by PUR and EPX, the most suiTable adhesive to use is EPX since it has better fill out capacity (Tlustochowicz, et al., 2010). Another research campaign by (Otero Chans, et al., 2010) that examined different types of adhesives also concluded that epoxy-based adhesive was the most suiTable for GiR connections, both in terms of strength and for suitability for production. Furthermore, EPX is the most common used adhesive, according to a survey filled out by scientists and representatives and designers from the timber industry (Stepinac, et al., 2013).

2.1.3 Rods

The most common material of the rod is steel, which in addition to high strength, provides the connection with ductile failure mode. Ductile behaviour is preferable since it gives an indication of failure before it happens, unlike brittle failure which occur without any warning (Tlustochowicz, et al., 2010).

Different types of steel rods, e.g. threaded and smooth, and with varying geometry, e.g. diameter and length, have been the subject of research (Tlustochowicz, et al., 2010). Threaded bolts are according to (Johansson, 1995) superior to smooth, since it is easier to achieve sufficient adhesion and gives an increased surface area for the adhesive, as well as mechanical interlocking. Threaded steel rods also make the assembly easy, as the rods can be connected to steel elements with washers and nuts.

There have also been several studies that investigated other materials than steel for rods in GiR joints. For example; hardwood, composite materials such as carbon fibre and glass fibre reinforced polymers (CFRP and GFRP). The advantages of hardwood rods are that the rod material and the load carry element have similar modulus of elasticity and similar moisture movements. While Rods made from FRP have the advantages that it can be used to produce lightweight structures, since FRP has high strength-to-weight ratio, which also gives FRP installation and transportation benefits. Another benefit with FRP is that the material is not sensitive to corrosion. However, the cost of FRP rods are higher than that of steel and therefore it is not used as much (Steiger, et al., 2015). Another disadvantage with FRP rods is that they exhibit brittle failure mode, and therefore do not give any indication of failure before it happens.

2.2 Application

GiR connection have many applications, e.g. column foundations, moment-resisting connections in beams and for frame corners (Steiger, et al., 2015).
Figure 2.2 illustrates application of GiR at pillar foot, between beams and pillars, as reinforcement for punching and as reinforcement for hooks.

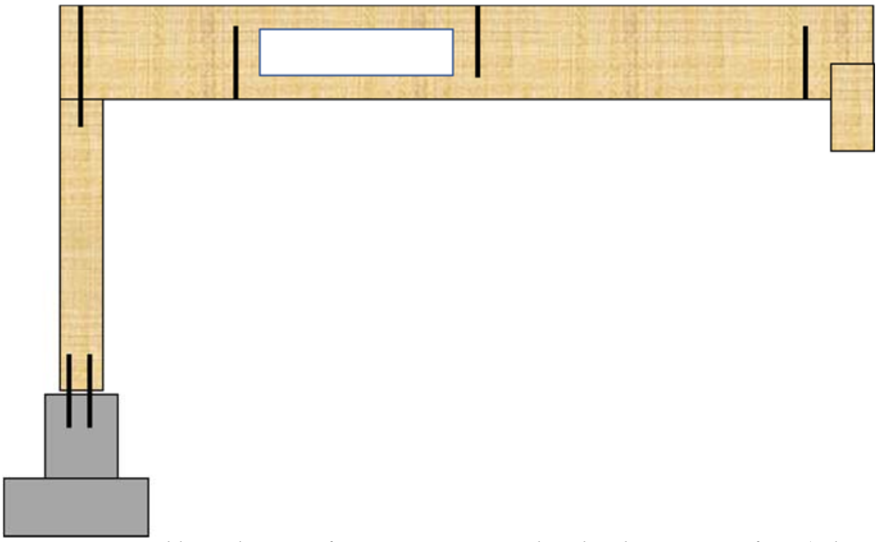

Figure 1.2 Possible applications for GiR. Image reproduced with inspiration from (Fili, 2015)

Furthermore, GiR connections can also be used as a sufficient method for repairing and reinforcing existing decayed timber elements (Alam, et al., 2009).

Connections with GiR have many advantages. The embedment of the steel rods in timber gives aesthetic qualities as well as protection against fire and corrosion (Gonzales, et al., 2016). Mechanical advantages of GiR include reliable strength under regular conditions, high local force transfer, relatively high stiffness and the possibility of ductile behaviour. Production advantages are reasonable cost, and relatively easy production and site assembly (Batchelar & Fragiacomo, 2012).

The disadvantages of GiR includes the limitations of timber, in-situ, brittle failure modes, difficulties to check and ensure proper execution and lack of design criteria.

2.3 Manufacturing

2.3.1 Assembly methods

There are several methods available for the assembly of GiR joints, but the first basic steps are similar. First a hole is drilled in the timber element, the diameter of the hole is usually a few millimetres larger than the diameter of the rods, since most adhesive perform better with reduced glue thickness, as this among other things reduces the risk of air bubbles which decreases the strength. Another advantage of a thinner adhesive thickness is that less glue is needed which reduces the cost (Steiger, et al., 2015).

The next step after drilling is to clean the borehole of particles that can reduce the strength of the adhesive; which can be done with compressed air (Steiger, et al., 2015).

The next step, which is the insertion of the rod, varies between methods. The simplest method is to fill the hole with a predetermined amount of adhesive and thereafter insert the rod, illustrated in Figure 2.3. The force that is needed for the insertion of the rod depends on the viscosity of the adhesive. The downside with this method is that it is impossible to control if the adhesive is evenly spread and if there are any air voids (Steiger, et al., 2015).

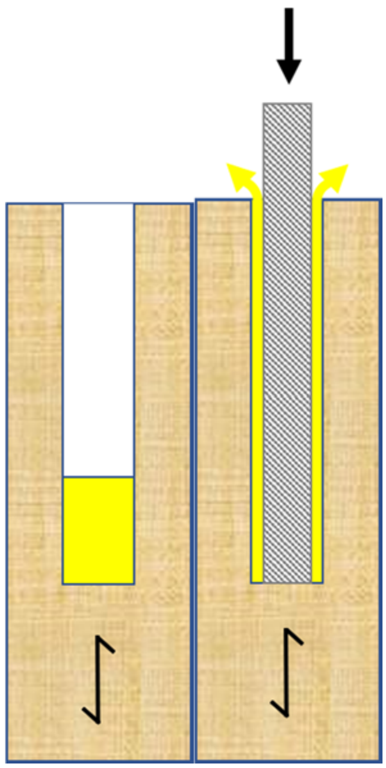

Figure 2.3. Simple insertion of the rod. Image reproduced with inspiration from (Steiger, et al., 2015).

Another available method is to drill two additional small holes perpendicular to the timber element, one at the bottom of the rod and one near the top. Then insert and fix the rod in the hole and then inject the adhesive through the bottom hole until it flows out from the top hole. The overflow of the adhesive indicates that the hole is filled. This method is illustrated in Figure 2.4. However, this method is only suiTable for joints with few rods. When more rods are required, then different assembly methods can be combined (Tlustochowicz, et al., 2010).

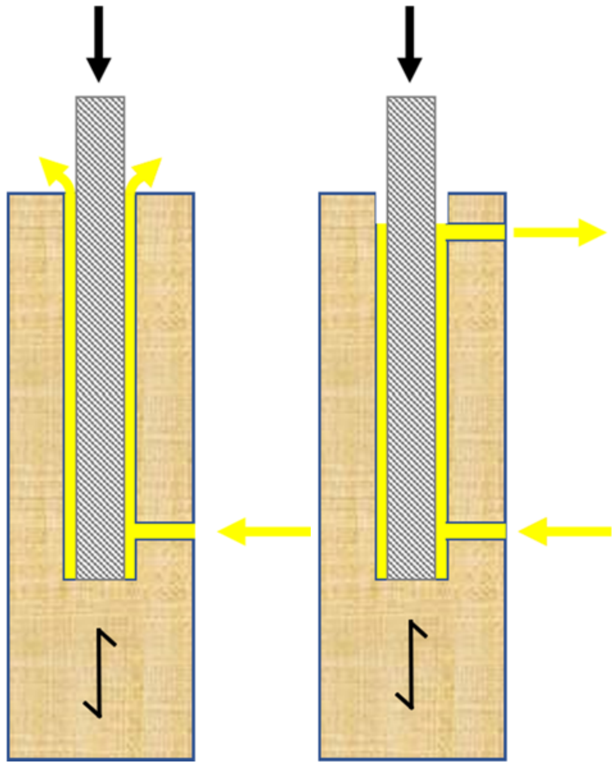

Figure 2.4. Assembly method with two holes drilled perpendicular to the timber element. . Image reproduced with inspiration from (Steiger, et al., 2015).

A third available method is to first brush glue on the rod to ensure the adhesion of the screws and then fill the hole with adhesive, and finally insert the rod and fix it in a centred position until the glue has solidified. This method is good when using several rods, however, it is time consuming and costly and therefore seldom used in practice.

2.3.2 Control methods

To ensure a high quality of a GiR connection, the parameters in Table 1.1 should be checked (Steiger, et al., 2015). This reduces the risk of different production errors, a-e, which are illustrated in Figure 2.5.

Table 2.1. Control parameters to ensure the quality of a GiR connection

Hole:	Position, diameter, depth, inclination, straightness, cleanliness
Rod:	Correct and centred positioning of the screw in the hole and if necessary use plugs to ensure centering (see Figure)
Adhesive:	Application according to manufacturers' specifications, control of filling level, occurrence of voids

a) Angular drilling, can be avoided by using drill jigs.
b) Oblique screw, can be avoided by using centering tools
c) Rod positioned along one side of the borehole, can be avoided by using centering tools
d) The rod has not reached the bottom, can be prevented by pushing in the screw with sufficient force or attaching a weight to it which allows the rod to reach the bottom before the adhesive cures.
e) Unwanted air gaps in the glue which reduces the strength. Can be avoided by rotating the screw during insertion or by brushing the glue on the rod and fill the hole with a sufficient amount of glue.

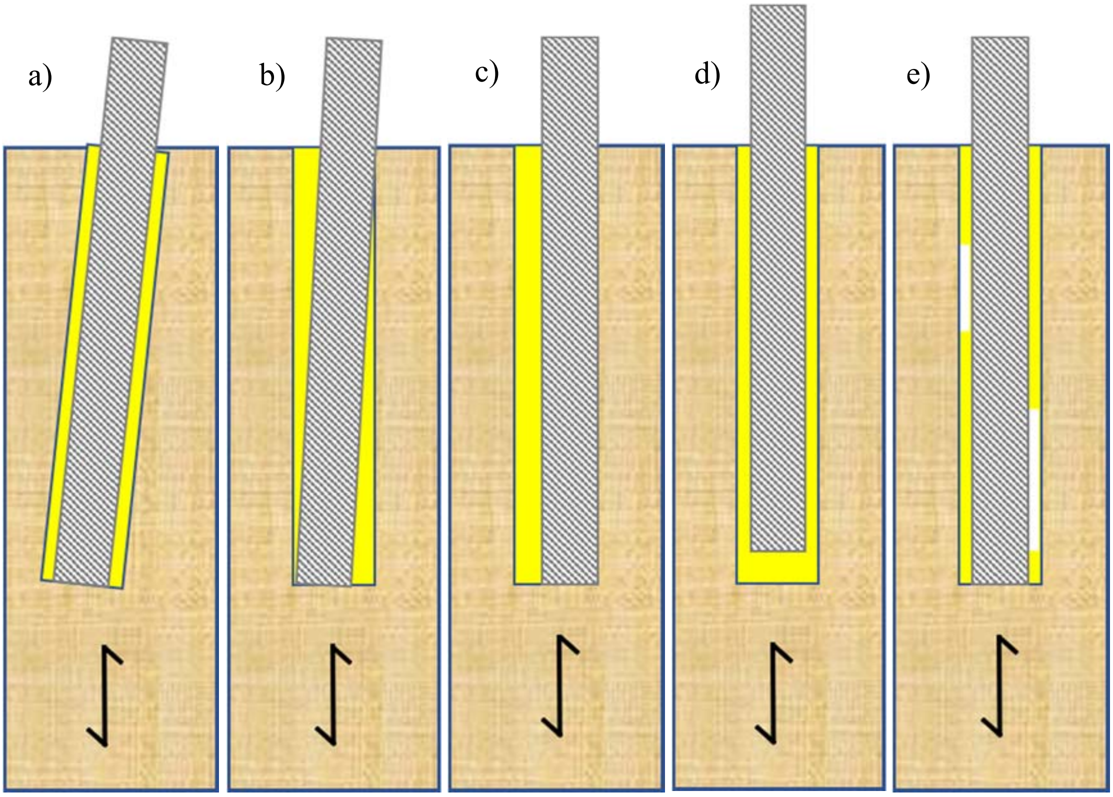

Figure 2.5. Common production errors for GiR. . Image reproduced with inspiration from (Steiger, et al., 2015).

3 Mechanical behaviour of GiR

In this chapter the parameters that affect the mechanical behaviour of GiR are presented and discussed. The most influential parameters can be classified into three main groups: geometry, material, and loading and boundary conditions. Furthermore, these main groups all have sub categorizes. The parameters are presented in Figure 3.1 (Serrano & Steigler, 2008).

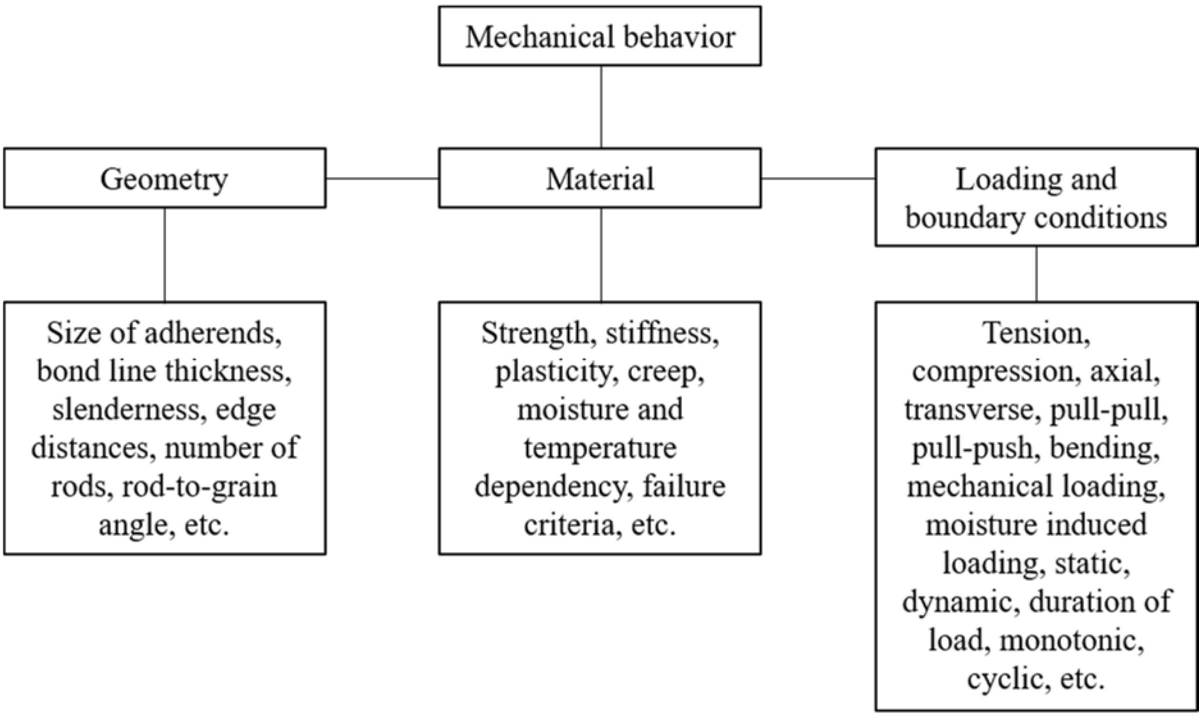

Figure 3.1. Mechanical behaviour of GiR. Image reproduced with inspiration from (Serrano & Steigler, 2008).

3.1 Geometry

In this sub chapter the geometrical parameters anchorage length, diameter of rod and hole, slenderness, thickness of the adhesive, rod-to-grain angle and edge distance, are presented and discussed.

Research by (Broughton & Hutchinson, 2001) showed that short anchorage length is associated with high stress concentrations which affects the GiR joint’s performance in a negative way. In earlier design suggestions, e.g. (Riberholt, 1988), the strength of the joint increased linearly with the anchorage length of the rods. The studies of (Steiger, et al., 2007) also showed an increase of the ultimate load with higher anchorage lengths, and a decrease in nominal shear strength. The research of (Yeboah, et al., 2011) showed that the increase comes from an enlargement of the bonded area at the interfaces between timber and adhesive as well as rod and adhesive which leads to a decrease in interfacial shear stress. Finally, research made by (Otero Chans, et al., 2013) showed an initial increase in failure load with higher anchorage length, but after a certain length the increase ceased and, in some cases, even a decrease of failure load was noted, which suggests that the increase is non-linear.

The research of (Broughton & Hutchinson, 2001) concluded that an advantage with the usage of rods with larger diameters is that the shear stress at the interface between the rod and the adhesive will be lower thanks to a larger bond area, and this might reduce the risk of failure. The studies of (Otero Chans, et al., 2008) showed an increase in load capacity with increased rod diameter, but the relationship was not proportional and difficult to define. The results of

(Steiger, et al., 2007) indicated the ultimate load increased with the diameter of the bore hole, however, the influence over the pull-out strength could not be confirmed. In other words, no conclusion has been reached on how the diameter of the rod and of the bore hole influence a GiR connection, even though they are commonly investigated parameters.

Since the parameters of anchoring length and diameter of the rod and borehole often interact with each other, a combination of the parameters, called slenderness, is regarded as a legit approach (Steiger, et al., 2007). The slenderness, λ, is the ratio between the anchorage length and the diameter of the rod. For example, (Rossignon & Espion, 2008) have used this approach and concludes that the total pull-out strength increases with higher slenderness. Experimental research conducted by (Otero Chans, et al., 2013) indicates that failure occurred at higher average shear stress values for GiR joints with lower slenderness. The study also suggested that GiR joints made with timber with higher density are less affected by the slenderness of the joint. For parallel glued rods the average shear stress decreases as the slenderness increases. The results correspond to tensile strength that increased with increasing glue length, however the increase was not directly proportional to an increase in the contact surface between timber and adhesive. For rods glued perpendicular to the grain, the behaviour is different from that of parallel rods as the shear stress is constant and independent of the slenderness of the joint (Rossignon & Espion, 2008).

The thickness of the adhesive is dependent on the diameter of the hole and the rod. If the hole is smaller than the diameter of the rod, the adhesive loses its function, and the strength of the connection is governed by the mechanical interaction between the timber and the rod (Steiger, et al., 2015). An increased thickness of the adhesive leads to an increased surface area between the timber and the adhesive but that does not improve the strength significantly. An increased surface area can instead be achieved by using a rod with greater diameter. (Martín, et al., 2013). The studies of (Broughton & Hutchinson, 2001) concluded that an increase of the amount of adhesive is not proportional to higher load capacity. There are not yet any general conclusion on how the thickness of the adhesive affects the strength of the joint, but it can be concluded that it depends on the properties of the adhesive that are used.

For the parameter rod-to-grain angle it is relevant to underline that a change of the angle often means a change of loading and boundary conditions and thus might make the comparison of perpendicular and parallel directions irrelevant (Tlustochowicz, et al., 2010). Furthermore, changes in direction will affect the effective moduli of elasticity for the timber and it is likely that the adhesion of the glue to the timber differs between direction since the borehole's surface is dependent on the orientation of the grain (Serrano, 2000). Timber is strongest in the longitudinal direction and it would therefore be reasonable to assume that GiR joints placed in that direction would have higher strength and there are studies that indicate this such as (Gustasson & Serrano, 2001). However, when the results of the studies (Widmann, et al., 2007) are compared with (Steiger, et al., 2007), the rods and anchorage length were the same, it was noticed that the mean pull-out strength of the GiR joints where higher when inserted perpendicular to the grain. Furthermore, (Otero Chans, et al., 2014) concluded that GiR joints set perpendicular caused larger deformations than those inserted parallel.

To get an optimal load transfer capacity of the GiR connection, the cross-section of the timber should be as small as possible, however the research of (Steiger, et al., 2007) indicated a reduction of the pull-out strength for GiR connections with small edge distances. These results are confirmed by (Otero Chans, et al., 2013) and in the same study it was also suggested that too short edge distance can cause splitting of the wood. The recommended edge distances vary from 1.5 up to 4 times the rod diameter, dependent on the design approach (Otero Chans, et al., 2010).

3.2 Material

In this sub chapter, the influence of the material properties of wood, glue and steel in the GiR connection is discussed.

For timber specimens with defects like knots and dry splits, experimental results indicate that there is no noticeable relation between the type of failure and the location of the defects or a weakening of the joint's strength caused by defects (Rossignon & Espion, 2008).

Early design approaches suggest that there is a linear relationship between timber density and load bearing capacity, however, in the research of (Rossignon & Espion, 2008) the conclusion that the failure loads of specimens with identical geometric characteristics don't have a linear relationship with the density and axial strength was reached. That the relationship between the failure load of the joint does not change linearly with the physical properties of the timber was concluded in the studies of (Otero Chans, et al., 2010).

Moisture movements in timber can cause stresses, cracking and loss of adhesion; and it is therefore suggested that GiR joints should be used in service class 1 and 2 and with caution or not at all in service class 3 (Johansson Jänkänpää, 2008). The strength of the adhesive can also be affected by the moisture content, however the effect varies between different types of adhesive. For example, in the studies of (Aicher & Dill-Langer, 2001), a decrease in strength was noted for the adhesive types PRF and PUR caused by humid conditions while EPX was relatively unaffected. GiR joints exposed to high moisture levels, like in the studies of (Johansson Jänkänpää, 2008), showed a substantial loss of pull-out strength. Other more recent studies like, (Verdet, et al., 2017), also showed that variations in moisture content can cause damage to GiR connections.

The type of adhesive affects the pull-out strength of the entire connection and the bonding strength of the adhesive is affected by type of timber, shrinkage during initial hardening, temperature, gap-filling qualities, and its sensitivity to ambient moisture content (Steiger, et al., 2015). The studies of (Dill-Langer, 2001) showed that the capacity of epoxy-based adhesives did not change particularly much, either in the long or short term, at different surrounding moisture levels. However, their tests also showed a decrease in strength for loaded epoxy-based adhesives subjected to temperatures above 50 degrees Celsius, while a certain increase could be noted for the short-term strength if the specimens were not loaded. While the experiments carried out in the studies of (Lartigau, et al., 2015) indicates that there is an appreciable decrease of stiffness and load bearing capacity for GiR connections when the temperature is above 60 degrees Celsius. The decrease in strength comes from irreversible modifications of the inner structure of the polymer that affects the mechanical properties of the adhesive, and therefore the whole connection. Temperature does also govern the global creep behaviour of GiR joints according to research carried out by (Verdet, et al., 2017).

The characteristics of the rod has a big impact on the failure mode of the joint; if it is brittle or ductile. For lower-grade steel rods, there is a higher chance of achieving ductile behaviour; however, sufficient unbonded length of the rod is required for allowing plastic deformations. Furthermore, high-strength steel rods are not recommended for steel-to-timber connections with multiple glued-in rods as their high-strength limits the redistribution of load between rods, and any imperfections during production of the connection may result in much lower capacity than the predicted value (Gattesco, et al., 2017).

3.3 Loading and boundary conditions

The loading situation determines the importance of the adhesive, if the connection is subjected to an axial load, Figure 3.2a, then the strength of the adhesive determines the capacity of the connection. If the connection instead is subjected to shear loading, Figure 3.2b, the role of the adhesive is less important, and the capacity of the joint is instead determined by the properties of the timber.

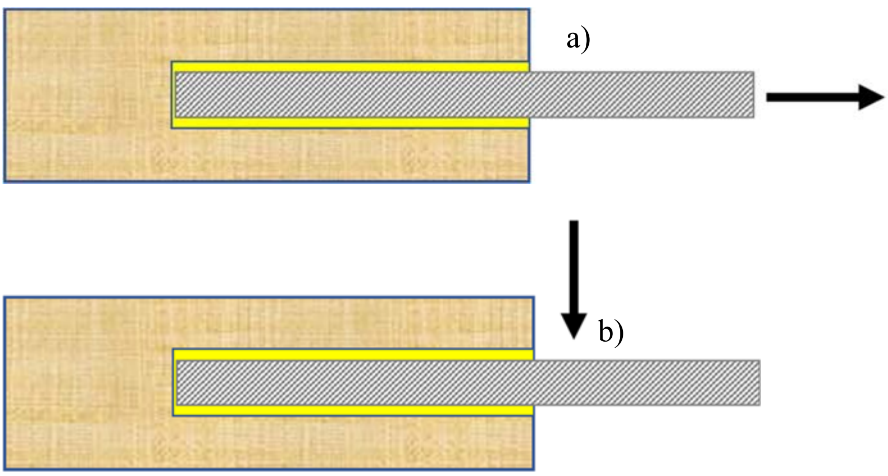

Figure 3.2. Different loading situations for GiR. Images reproduced with inspiration from (Fili, 2015).

GiR connections with a single rod is not so common in practice but using them for tests makes analysis of isolated parameters and their influence on the mechanical performance possible (Tlustochowicz, et al., 2010). Different loading situations are used when conducting experimental research on GiR connections with single. For rods set parallel to the grain, the main test set up is a pull-pull configuration, Figure 3.3 (Steiger, et al., 2007).

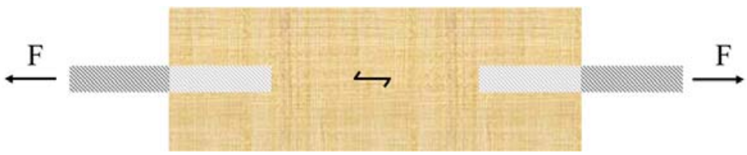

Figure 3.3. Pull-pull loading case for GiR. Image reproduced from (Steiger, et al., 2015).

While for rods inserted perpendicular to the grain, there are three different types of loading configurations commonly used; pull-compression (Fig. 3.4a), pull-beam (Fig. 3.4b) and pull-pile foundation (Fig. 3.5). However, the pull-compression situation has a poor correlation with reality and there is also a risk that local compression stresses in the load applied area might influence the pull-out strength. The pull-beam configuration has a better correlation with reality but has the disadvantages that it requires a lot of glulam, and there is a risk of introducing bending stresses. The third option, pull-pile foundation set up, has the advantage that that tensile forces in the rod is balanced by shear stresses in the timber (Widmann, et al., 2007).

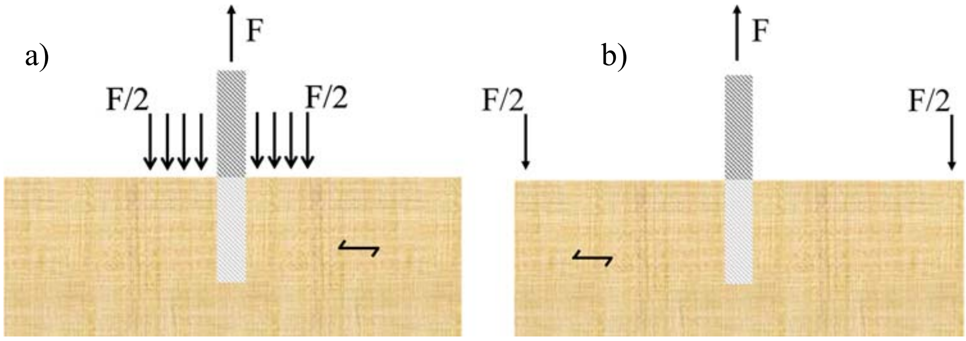

Figure 3.4. Pull-compression and pull-beam loading case for GiR. Image reproduced with inspiration from (Steiger, et al., 2015).

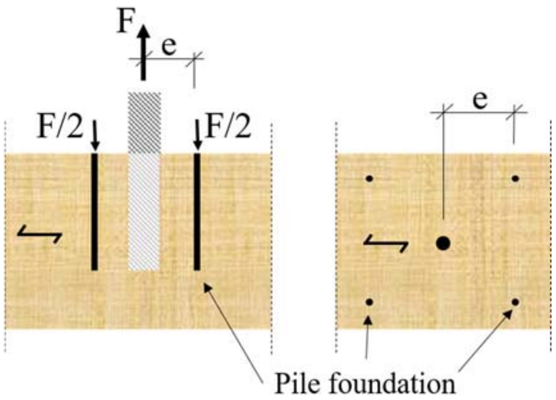

Figure 3.5. Pull-pile foundation loading case for GiR. Image reproduced from (Steiger, et al., 2015).

Other loading and boundary conditions have also been studied. For example, long term effects were studied in (Damkilde, et al., 1999) and the observations drawn from their experiments were no difference in residual strength as a function of the load history, that the mean strength of the bolts correlated with the predicted short-term static strength and finally that their investigated bolts maintained full strength after 9 years in situ loading. While (Xu, et al., 2012) focused on GiR joints loaded in bending and developed two analytical models for prediction of the initial stiffness and the bending strength. Furthermore, (Gattesco, et al., 2017) performed monotonic bending tests that showed that it is possible to obtain a ductile failure mode of the GiR joint, with the right choice of the steel rods and edge distances. And finally, (Molina, et al., 2009) carried out static and cyclic tests on GiR connections and concluded that an increased in loading significantly reduced the number of cycles to failure.

3.4 Force transmission

For screws, the load bearing capacity depends on the anchoring capacity of the washers and nuts, the tensile strength of the screws (Borgström, 2016), as well as the compression mechanism created by contact between the wood and the screw flanks (Tlustochowicz, et al., 2010). However, screws and GiR have different mechanical behaviour, since for GiR the shear surface is continuous along the rod, while it is divided into segments which cannot transfer shear stress for screws (Jensen, et al., 2010).

Some research projects suggest that the anchorage between the rod and the adhesive acts like a mechanical joint (Deng, 1997), while other that the connection behaves like a combination of mechanical and glued connections (Widmann, et al., 2007). If the hole is smaller than the diameter of the rod, there is no room for the adhesive, and the strength of the connection is governed by the mechanical interaction between the timber and the rod (Steiger, et al., 2015). And if not, the transfer of forces through the glue layer and the layer between the glue and the wood consist of shear. For the load situation in focus in this thesis, axial loading, the adhesive layer wants to follow the rod as it is pulled, which causes so called "peel stresses" perpendicular to the rod. These stresses acts in compression in the bottom of the joint and in tension close to the unrestricted surface for the adhesive layer. While the stress direction in the timber is the opposite; compression close to the unrestricted surface and tension in the bottom (Gonçalves, et al., 2014).

3.5 Failure modes

The failure modes related to GiR joints are influenced by the materials in the connections, their mechanical properties, geometrical dimensions and the properties of the bond between the material. The ultimate strength of the connection depends on the weakest link of the joint. For axially loaded connections, (Steiger, et al., 2015) mentions different failures modes illustrated in Figures 3.6-3.13. However, failure modes do not always occur in an individual manner, but rather often combined. A common example is that failure by shear stresses often are accompanied by timber splitting (Otero Chans, et al., 2010).

1. Failure of the rod due to either material failure, e.g. yielding of steel, or by buckling of the rod if loaded in compression.

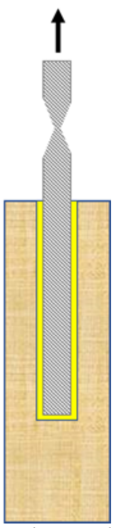

Figure 3.6. Failure of the rod. Illustration done with inspiration from (Feldt & Thelin, 2018)

2. Pull-out of the rod which depends on the adhesive as well as its adhesion to the steel and timber, thus can this failure mode be divided into four different possible cases.

   a. adhesive failure at the steel-adhesive interface due to either shear failure in the case of smooth rods or crushing of the adhesive in the case of threaded rods.
   b. cohesive failure (shear) in the adhesive
   c. adhesive failure (shear) at the interface between the timber and the adhesive
   d. cohesive failure (shear) in the wood close to the adhesive layer

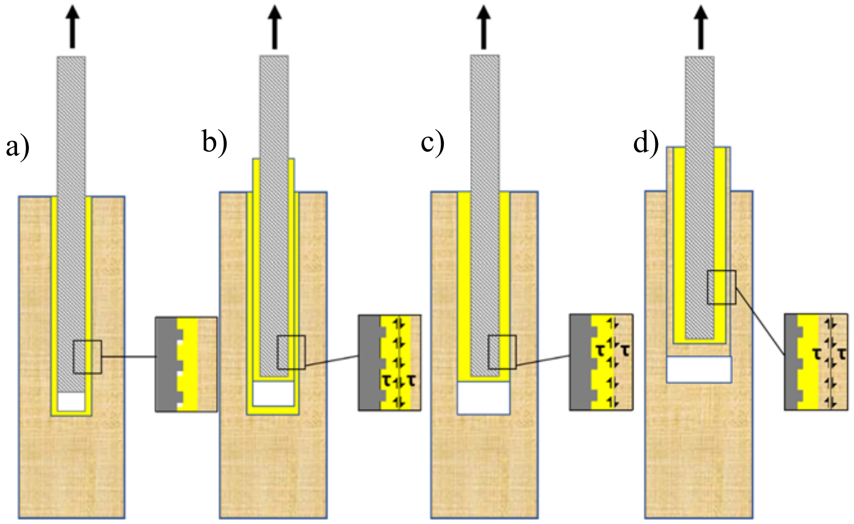

Figure 3.7. a) adhesive failure at the steel-adhesive interface, b) cohesive failure (shear) in the adhesive, c) adhesive failure (shear) at interface between the timber and the adhesive, d) cohesive failure (shear) in the wood close to the adhesive layer. Illustration done with inspiration from (Feldt & Thelin, 2018)

3. Pull-out of wood plug due to shear failure in the timber parallel to the grain.

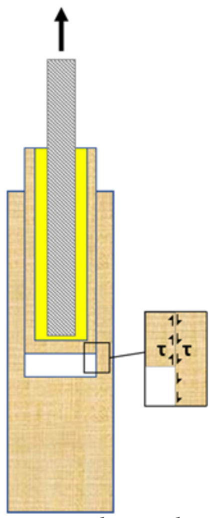

Figure 3.8. Pull-out of wood plug. Illustration done with inspiration from (Feldt & Thelin, 2018)

4. Splitting failure of the timber due to either too short edge distances, or stresses induced between rod and grain.

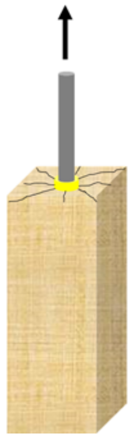

Figure 3.9. Splitting of timber. Illustration done with inspiration from (Feldt & Thelin, 2018)

5. Tensile failure in the timber cross-section due to inserted and loaded rod perpendicular to the timber.

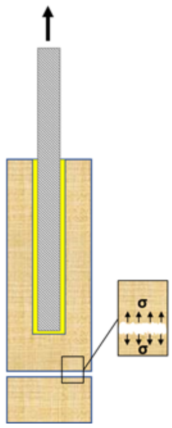

Figure 3.10. Tensile failure in the timber cross-section. Illustration done with inspiration from (Feldt & Thelin, 2018)

In addition to these failure modes for single-rod connections, the following are of interest for multiple rod connections:

6. Splitting failure between the rods due too short distances between the rods

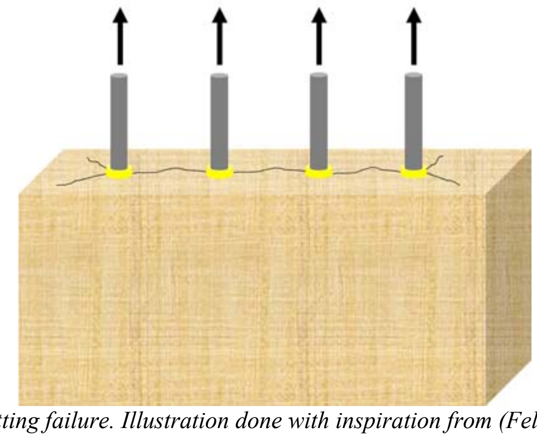

Figure 3.11. Splitting failure. Illustration done with inspiration from (Feldt & Thelin, 2018)

7. Group pull-out caused by shear failure in the timber

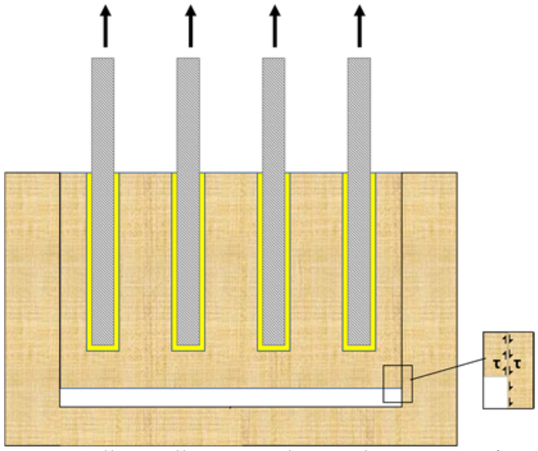

Figure 3.12. Failure by group pull-out. Illustration done with inspiration from (Feldt & Thelin, 2018)

Some failure modes are easier to predict and prohibit than others. Failure mode 1, steel failure, can for example be prevented with sufficient steel strength for the current load situation. While failure modes 4 and 5, splitting failure of the timber and tensile failure in the cross-section of the timber can be prohibited with adequate edge distances and cross-section area of the timber.

Failure modes 2 and 3, shear failure associated with the pull-out strength of the rod, are however more difficult to assess and the failure mode studied in this thesis. From previous studies, it can be concluded that the pull-out capacity depends primarily on the interfacial layer and shear strength parameters which are influenced by the mechanical and geometrical properties of the three different materials used in a GIR connection (Stepinac, et al., 2013). Furthermore, the behaviour and mechanism of failure at the adhesive bond-line is similar between single and multiple GiR, which means that conclusions drawn from studies on single GiR can be applied to GiR joints with multiple rods

3.6 Analysis methods of the adhesive bond strength

There are three types of theoretical approaches traditionally used for analyses of the adhesive bond line; traditional strength analysis, linear elastic fracture mechanics (LEFM) and non-linear fracture mechanics (NLFM). The choice of theory depends on the assumed failure type, size, stiffness, and shape of the connection and its elements.

Traditional strength analysis estimates how the stress is distributed in the joint for a certain loading situation. This is achieved by applying failure criterion on the force distribution which will give a prediction of the load bearing capacity and stiffness of the joint. (Tlustochowicz, et al., 2010)

In LEFM the loading situation of the joint consists of a pre-existing crack and the failure criterion used is either the energy release rate or a stress intensity factor. The critical energy release rate of the joint is the amount of energy needed to increase the crack area. The material is characterized by a corresponding critical energy release rate or a critical stress intensity factor. (Serrano & Gustafsson, 2007)

In NLFM, the traditional approach of a stress–strain relation, is substituted to a non-linear stress–displacement relation by assuming a non-linear softening behaviour of the bond line. The advantages of this approach are that both the strength of the bond line and the fracture energy of the joint can be accounted for (Tlustochowicz, et al., 2010). However, this sort of analysis requires knowledge of the fracture energy of the materials and the assumption that the degree of anisotropy of the species is constant (Coureau, et al., 2016).

4 Methodology of the work

This chapter describes the working methodology, the selection process for design equations and experimental results, and the calculations made. The chapter also contains a discussion of the methodology.

4.1 Selection process

Previous studies like (Tlustochowicz, et al., 2010) compared different design proposals by applying the same input to selected equations and plotted the result. In this work however, another approach was used, selected design proposals were compared with experiments.

The choice of design equations to study was initially based on the report written by (Stepinac, et al., 2013) which contains a list with 17 design proposals for calculating the pull-out strength of a single GiR from different year, countries and authors. However, the possible application and what the equations calculated varied too much for a direct comparison between these 17. Therefore, the different equations were studied and five that were compatible with each other were selected. These five were then supplemented with a design proposal from (Otero Chans, et al., 2013), which meant that in total six design proposals were studied and compared in this work.

The collection of test series for comparison was done during the literary study, where articles containing experiments were selected. Requirements and limitations were then determined for the test series to enable comparison with the chosen design equations. Which meant that for articles containing experimental studies the following requirements of the test set up needed to be fulfilled:

- Type of rod: threaded rods made of steel
- Angle between rod and grain: parallel or perpendicular
- Type of adhesive: Epoxy
- Type of timber: Glulam or sawn timber
- Type of density for the timber: characteristic
- Type of loading: Axial

After the establishing of these limitations, seven research articles that contained experimental data were chosen for comparison. The capacities of the test specimens were also plotted versus anchorage length and slenderness, respectively, to give an overview of the results.

4.2 Calculation method

The input data from the various experiments were applied to the selected design proposal, and a theoretical capacity was calculated. After that, a ratio between the theoretical capacity and the experimental values were calculated, $F_{k,criteria}/F_{k,test}$.

For each design proposal, two scatter plots were made, where the ratio, $F_{k,criteria}/F_{k,test}$, was plotted versus either the anchorage length or the slenderness. A distinction between tests performed on either hardwood or softwood was made to see which of these two timber categories that corresponds best with the design proposals. Two additional plots were then made with linear approximations based on the previous made scatter plots to clarify and simplify the comparison between the design equations.

4.3 Discussion of methodology

For the selected method to work and be relevant, it was necessary that the different design proposals calculate the same thing and can be compared to experimental results. This limited both the number of design proposals and the number of experimental studies, which affects the statistical relevance of the work in a negative way. Since the aim was to find a calculation model that can be applied to different types of wood, it is justified to have data from tests on different timber types, softwood and hardwood, and mark the difference for easier comparisons. However, all test series with hardwood timber found in literature had anchoring lengths less than 200mm.

Furthermore, only GIR joints with the adhesive type epoxy was investigated. This was motivated by the fact that it is the most commonly used adhesive type, but there are other types on the market. The same applies to the choice of rod material, threaded steel, which is the most common, but there are other interesting options. And finally, there were considerably more test specimens where the rod was glued parallel to the grain than perpendicular, and no cases with a different angle than 0 and 90.

5 Data and equations

In this chapter, the parameters and the test data from the chosen experimental studies and design equations are presented.

5.1 Test series

The material and geometric parameters for the chosen test series are presented in Table 5.1. The material and type of the rod and the adhesive were consistent for all tests, while the type of timber varied.

Table 5.1. Mechanical parameters for test series.

Article:	Wood species:	Type of wood:	Softwood/Hardwood:	Rod	Adhesive (1)
Steigler (2006)	Spruce	Glulam	Softwood	Threaded steel bar	2K EPX
Steigler (2007)	Spruce	Glulam	Softwood	Threaded steel bar	2K EPX
Otero Chans (2008)	Tali	Glulam	Hardwood	Threaded steel bar	2K EPX
Rossignon (2008)	Spruce	Glulam	Softwood	Threaded steel bar	2K EPX
Otero chans (2009)	Chestnut/Tali	Sawn timber	Hardwood/Hardwood	Threaded steel bar	2K EPX
Otero chans (2010)	Chestnut/Tali	Sawn timber	Hardwood/Hardwood	Threaded steel bar	2K EPX
Otero chans (2013)	Spruce/Eucalyptus	Glulam	Softwood/Hardwood	Threaded steel bar	2K EPX

(1) 2K EPX: epoxy based adhesive

The geometrical parameters for the chosen test series are presented in Table 5.2. The rod diameter and the anchorage length varied both within and between the individual experimental series. The density of the timber also varied between the tests.

Table 5.2. Geometrical parameters for test series.

References	d_r [mm]	l_a [mm]	ρ_k [kg/m3]
Steigler (2006)	12,16,20	105-330	349-485
Steigler (2007)	12,16,20	105-275	349-485
Rossignon (2008)	12, 16, 20, 24	120-600	> 380
Otero Chans (2008)	10, 12	60-180	796
Otero Chans (2009)	10, 12	60-180	470, 800
Otero Chans (2010)	10, 12	60-180	470, 800
Otero Chans (2013)	12	60-180	414, 734

The number of tests, loading configuration and angle between the rod and the grain, are presented in Table 5.3. One experimental study did not contain any information of the total number of tests, however, the sum of the rest is 916, which gives a good statistical basis. The dominating boundary condition is the pull-pull configuration, (P-P), and the other one is pull-foundation (P-F), and for most of the test specimens, the rod has been glued parallel to the grain.

Table 5.3. Number of test specimens and boundary conditions for test series.

References	Number of test specimens	Loading configuration	Angle to the rod
Steigler (2006)	120	P-P	Parallel
Steigler (2007)	86	P-F	Perpendicular
Rossignon (2008)	60	P-P	Parallel
Otero Chans (2008)	70	P-P	Parallel
Otero Chans (2009)	180	P-P	Parallel
Otero Chans (2010)	400	P-P	Parallel
Otero Chans (2013)	-	P-P	Parallel

5.2 Design proposals

Despite several different design equations and approaches, the basic principle for design is similar, and includes the parameters anchorage length, diameter of rod and a parameter that characterizes the shear strength of the rod/adhesive/timber interface (Stepinac, et al., 2013). Thus, a general simplified calculation model for axial loading can be summarized as:

$$R_{ax,k} = \pi * d * l * f_{v,k}$$

$R_{ax,k}$ = characteristic pull-out capacity

l = anchorage length

d = diameter

$f_{v,k}$ = shear strength parameter

The problem is to define a shear strength parameter that takes both the timber and the adhesive properties into account (Stepinac, et al., 2013), which is emphasized as it varies between different design equations. Furthermore, as the shear stress at maximum load typically varies along the anchorage length, the shear strength parameter commonly depends on the anchorage length. The chosen design proposals for studying are presented in sub chapter 5.2.1-5.2.6.

5.2.1 Riberholt (1988)

The design equation presented in eq. 5.1-5.2 comes from the studies of (Riberholt, 1988) and are based on the density of the timber and the geometry of the connection. The shear strength parameter, in this equation called the withdrawal parameter, varies with different anchorage lengths and types of adhesive. The design equation presented in eq. 5.1-5.2 is adapted for epoxy type adhesive, and may be used for all structures in moisture class 1 and 2 (Riberholt, 1988).

$$R_{ax,k} = f_{wl} * \rho_k * d * l_g \ for \ l_g < 200 \ mm \tag{5.1}$$

$$R_{ax,k} = f_{ws} * \rho_k * d * \sqrt{l_g} \ for \ l_g \geq 200 \ mm \tag{5.2}$$

$R_{ax,k}$ = characteristic axial resistance [N], [kN]
f_{wl} = withdrawal parameter for the linear case [N/mm^2] = 37
f_{ws} = withdrawal parameter for the square root case [N/mm$^{1.5}$] =520
ρ_k = characteristic density of the timber [kg/m^3]
l_g = glued in anchorage length [mm]
d = nominal diameter of the rod [mm]

5.2.2 Eurocode 5 (2001)

The design equation presented in eq. 5.3-5.5 was included in a draft of Eurocode 5 from 2001 (Otero Chans, et al., 2008) and is a conversion of an earlier suggestion from (ENV, 1997). It has the same theoretical structure as Riberholt's proposal, with the parameters; shear strength of the timber-adhesive interface, anchorage length and diameter and the density of the timber. However, correction factors have been added for the diameter and the density, and restrictions have been made for rods glued in parallel to the grain.

$$R_{ax,k} = \pi * d_{equ} * l_a * f_{v,\alpha,k} \tag{5.3}$$

$$f_{v,\alpha,k} = \frac{f_{v,90,k}}{sin^2\,\alpha + 1.5\,cos^2\,\alpha} \tag{5.4}$$

$$f_{v,90,k} = 1.2 * 10^{-3} * (d_{equ})^{-0.2} * \rho_k^{1.5} \tag{5.5}$$

$R_{ax,k}$ = characteristic axial resistance [N], [kN]

$f_{v,\alpha,k}$ = characteristic shear strength of the wood at the angle between the rod and grain direction
d_{equ} = equivalent diameter [mm], equal to the smaller of the hole diameter and 1,15 times the diameter of the rod
ρ_k = characteristic density of the timber [kg/m^3]
l_a = glued in anchorage length [mm]
α = the angle between the rod and the grain direction

5.2.3 Eurocode 5 (2003)

The design method presented in eq. 5.6-5.8 originates from (prEN, 2003) and was established from the basis of the research done during the GIROD project and especially from the results from tests performed by (Gustasson & Serrano, 2001). Following criteria should be taken into consideration when using this design equation (prEN, 2003):

1. The use of bonded-in rods should be limited to structural parts assigned to service classes 1and 2.
2. It should be verified that the properties of the adhesive and its bond to steel and wood are reliable during the lifetime of the structure within the temperature and moisture ranges envisaged.
3. Rods should be threaded or deformed bars.
4. The shear strength of the adhesive and its bond to steel and timber should be verified by tests.
5. For service class 2, the values of k_{mod} according to EN 1995-1-1 clause 3.1.3 should be reduced by 20 %

And, for rods in compression, the possibility of buckling should be taken into account for design compression stresses greater than 300 N/mm2.

$$R_{ax,k} = \pi * d_{equ} * l_a * f_{ax,k} \frac{\tanh \omega}{\omega} \quad (5.6)$$

$$\omega = \frac{0.016 * l_a}{\sqrt{d_{equ}}} \quad (5.7)$$

$R_{ax,k}$ = characteristic axial resistance [N], [kN]

$f_{ax,k}$ = characteristic shear strength [N/mm^2]
= 5.5 N/mm^2

d_{equ} = equivalent diameter [mm], equal to the smaller of the hole diameter and 1,15 times the diameter of the rod

ρ_k = characteristic density of the timber [kg/m^3]

l_a = anchorage length [mm]

ω = stiffness ratio of the joint

5.2.4 Feligioni (2003)

The design equation presented in eq. 5.8-5.9 originates from (Feligioni, et al., 2003) and is also based on (ENV, 1997) and has the same shear strength parameter as EC5 (2001). However, (Feligioni, et al., 2003) recognised that there is an increase in pull-out strength that comes from the energy accumulated during plastic deformation of the glue, which means that a greater volume of glue gives a higher capacity. Therefore, (Feligioni, et al., 2003), adjusted the equation to take the glue strength into account as well as the glue volume. It should be noted that the glue strength parameter, k, was derived from results from tests made with Norway spruce timber and a diameter of 12 mm (Feligioni, et al., 2003). Furthermore, the test configuration was pull-compression.

$$R_{ax,k} = \pi * l_g * (f_{v,k} * d_{equ} + k * (d + e) * e) \quad (5.8)$$

$$f_{v,k} = 1.2 * 10^{-3} * d_{equ}^{-0.2} * \rho_k^{1.5} \quad (5.9)$$

$R_{ax,k}$ = characteristic axial resistance [N], [kN]
$f_{v,k}$ characteristic shear strength of the wood [N/mm^2]
d = nominal diameter of the rod [mm]
d_{equ} = equivalent diameter [mm], equal to the smaller of the hole diameter and 1,15
ρ_k = characteristic density of the timber [kg/m^3]
l_g = glued-in anchorage length [mm]
e = glueline thickness [mm]
k = glue strength parameter, =0.086 for epoxy-based adhesive

5.2.5 DIN (2008)

The design equation presented in eq. 5.10-5.13 is from the German National annex of Eurocode (DIN, 2008). It is similar to Ribenholt's equation but is strictly geometrical and does not consider the density of the timber as a parameter. The values for the bond line strength are derived from test performed by (Blass, et al., 1996). The limitations of application is (Tlustochowicz, et al., 2010) : single glued-in rods, loaded axial in tension with a range of slenderness ratio between 7.5–15, a range of rod diameter between 12-20 mm, and glulam made of Norway spruce or other timber with similar properties and density in the range of 350–500 kg/m3.

$$R_{ax,k} = \pi * d * l_{ad} * f_{k1,d} \tag{5.10}$$

$$f_{k1,k} = 4.0 \qquad for\ l_{ad} \leq 250\ mm \tag{5.11}$$

$$f_{k1,k} = 5.25 - 0.005 l_{ad} \qquad for\ 250 \leq l_{ad} \leq 500\ mm \tag{5.12}$$

$$f_{k1,k} = 3.5 - 0.0015 l_{ad} \qquad for\ 500 \leq l_b \leq 1000\ mm \tag{5.13}$$

$R_{ax,k}$ = characteristic axial resistance [N], [kN]
$f_{k1.k}$ characteristic value of the bond line strength [N/mm^2]
d = nominal diameter of the rod [mm]
l_{ad} = glued-in anchorage length [mm]

5.2.6 Otero Chans (2013)

The design equation presented in eq. 5.14-5.16 is from the studies of (Otero Chans, et al., 2013) and is based on the average shear stresses of the joint, f_{joint}. Eq. 5.15 represents the shear strength of the joint for average slenderness (λ =10) while eq. 5.16 corrects the previous value depending on how great the influence of the slenderness is in relation to the wood species used. The equation is derived from tests with both hardwood and softwood timber, and the correction factor α was adapted to fit both (Otero Chans, et al., 2013). Furthermore, the study of (Otero Chans, et al., 2013) was done with the influence of the slenderness parameter which varied between from 5 to 18 and the rod was glued in parallel to the grain, see chapter 5.1 for a more precise test configuration.

$$F_k = f_{joint} * \pi * D * L \tag{5.14}$$

$$f_{joint} = 0.6 * \rho_k^{\alpha}\left(1 - \frac{0.7 * k^3}{\rho_k + k^2}\right) \tag{5.15}$$

$$k = \lambda - 10 = \frac{L}{d} - 10 \tag{5.16}$$

F_k	= characteristic axial resistance [N], [kN]
D	= diameter of the hole [mm]
d	= diameter of the rod [mm]
L	= glued-in anchorage length [mm]
ρ_k	= characteristic density of the timber [kg/m^3]
$0.6 * \rho_k^{\alpha}$	= shear strength of the joint for average slenderness λ=10

6 Results

In this chapter, scatter plots of the capacities of the test specimens is presented together with the results of the calculations in the work.

Figure 6.1 and 6.2 show how the capacity of the test specimens in the selected studies varies with anchorage length and slenderness, respectively. The filled points represent studies with test specimens with hardwood timber while those that are not filled with softwood. A general observation for both figures is that the capacity is in general higher for softwood specimens. and another that the capacity increases with longer anchoring lengths.

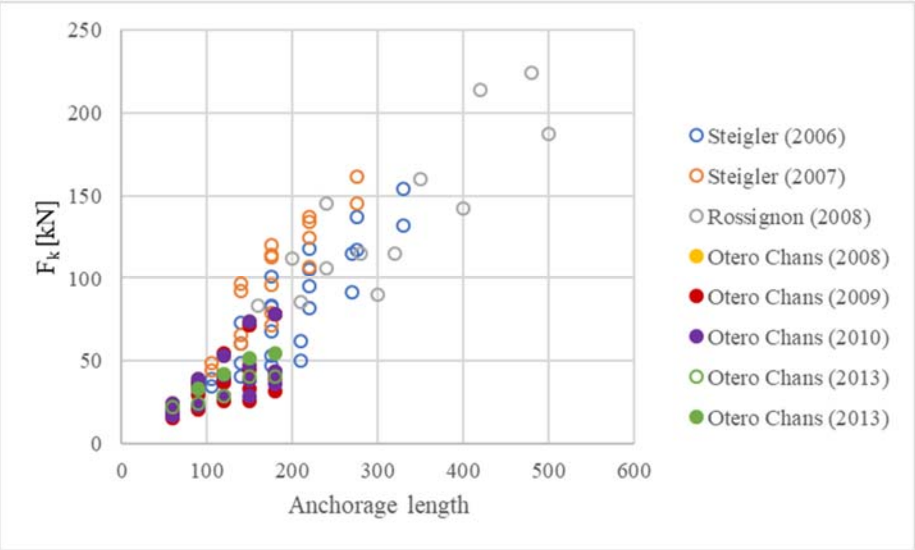

Figure 6.1. Scatter plots describing the correlation between the capacity of the test specimens and the anchorage length.. ●- tests on hardwood, ○-tests on softwood

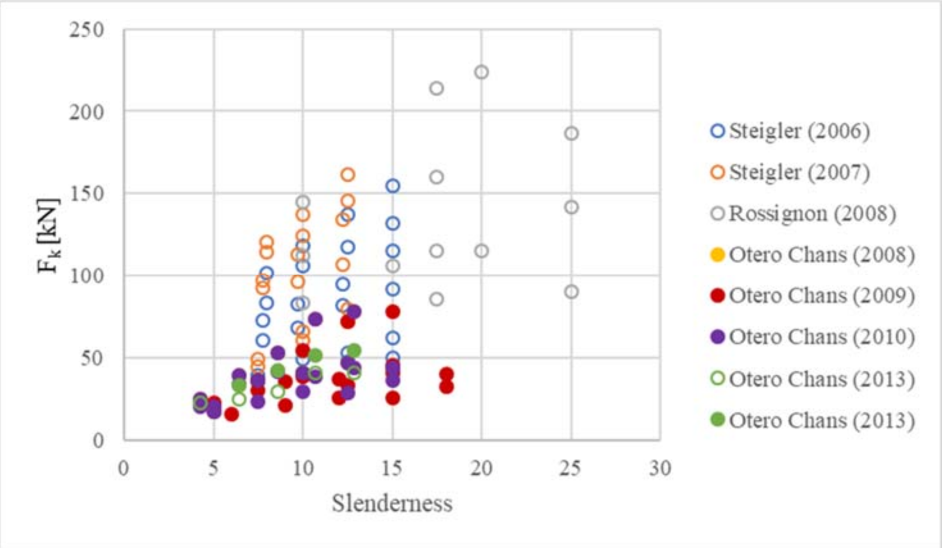

Figure 6.2. Scatter plots describing the correlation between the capacity of the test specimens and the slenderness. ●- tests on hardwood, ○-tests on softwood

Figure 6.3 and 6.4 each consists of six scatter plots were the ratio $F_{k,criteria}/F_{k,test}$ has been plotted versus the anchorage length and slenderness respectively for different design equations of the pull-out strength for axially loaded single Glued-in rods. If the ratio,

$F_{k,criteria}/F_{k,test}$, is equal to 1.0, it means that the theoretical value correlates with the test value in a perfect way. While a ratio higher than 1.0 means that the design equation overestimates the capacity of the joint, which poses a risk of construction failure. On the other hand, if the value is lower, the capacity is underestimated, and the design is on the safe side, but the lower the value, the less effective is the design equation. The plots were assembled and placed next to each other for a better overview. The points that are filled represent studies made with hardwood timber while those that are not filled with softwood.

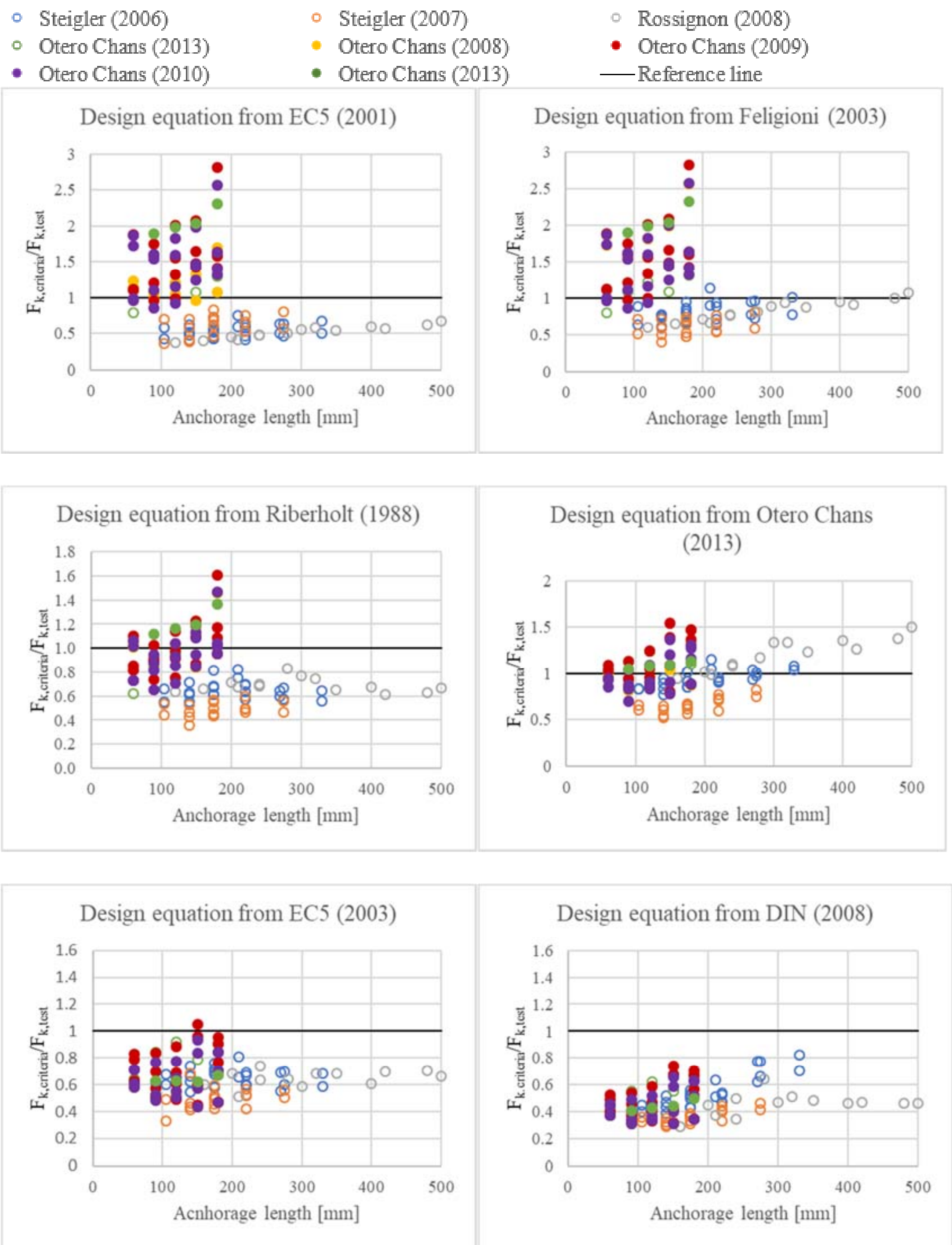

Figure 6.3. Scatter plots describing the correlation between the ratio, $F_{k,criteria}/F_{test}$ and the anchorage length for six different design proposals. ●- tests on hardwood, ○-tests on softwood. Note that the scales of the y-axes vary.

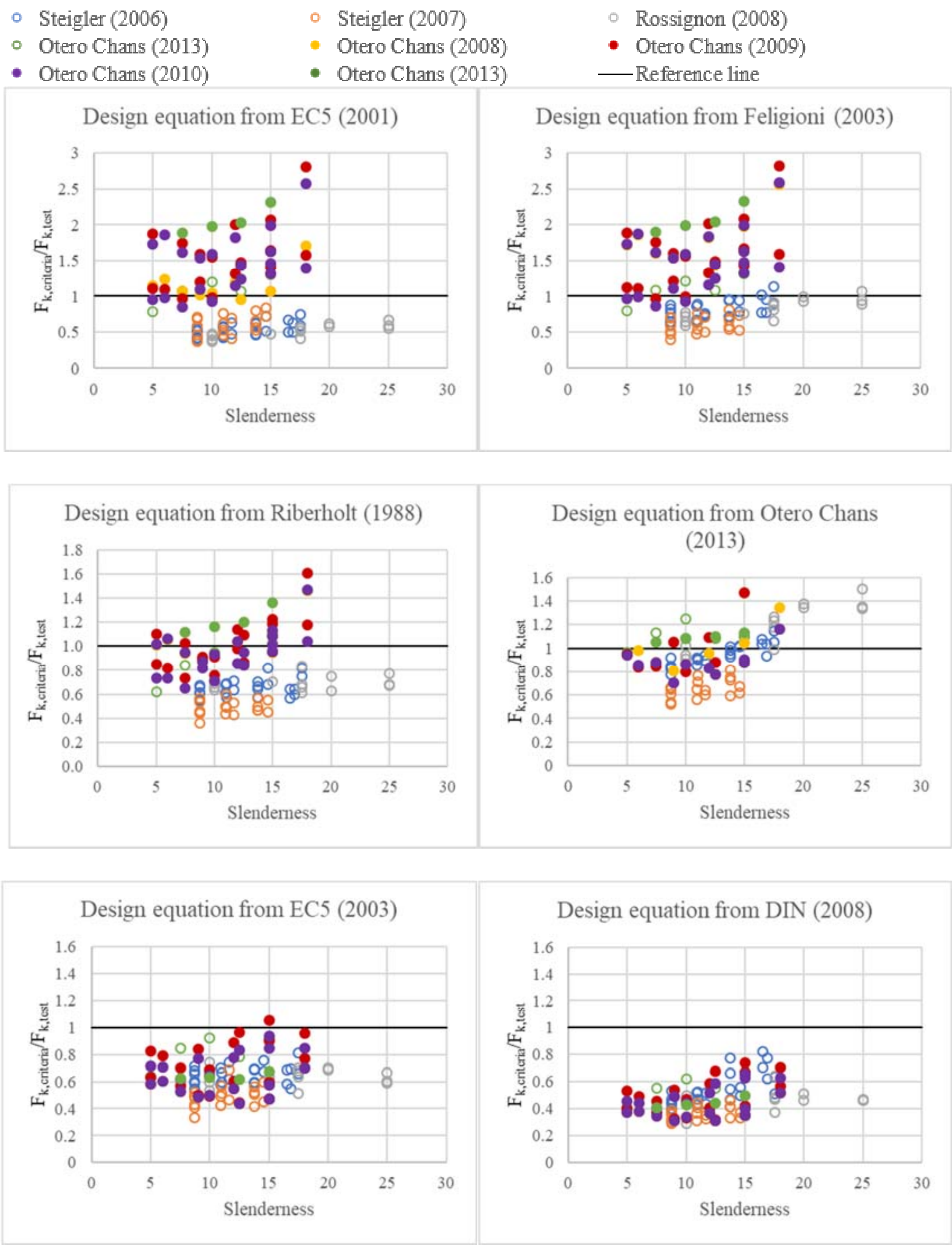

Figure 6.4. Scatter plots describing the correlation between the ratio, $F_{k,criteria}/F_{test}$ and the slenderness for six different design proposals. ●- tests on hardwood, ○-tests on softwood. Note that the scales of the y-axes vary.

Figure 6.5 and 6.6 show linear approximations of the six design equations based on the scatter points in Figure 6.3 and 6.4. The solid lines are for hardwood timber studies while the dotted are for softwood. The solid lines are shorter than the dotted, because the ratio $F_{k,criteria}/F_{k,test}$, is only plotted where it is valid, and there were no test specimens with longer anchorage lengths than 180 mm for hardwood timber. A general observation is that the ratio, $F_{k,criteria}/F_{k,test}$,, increases with higher anchorage lengths and slenderness.

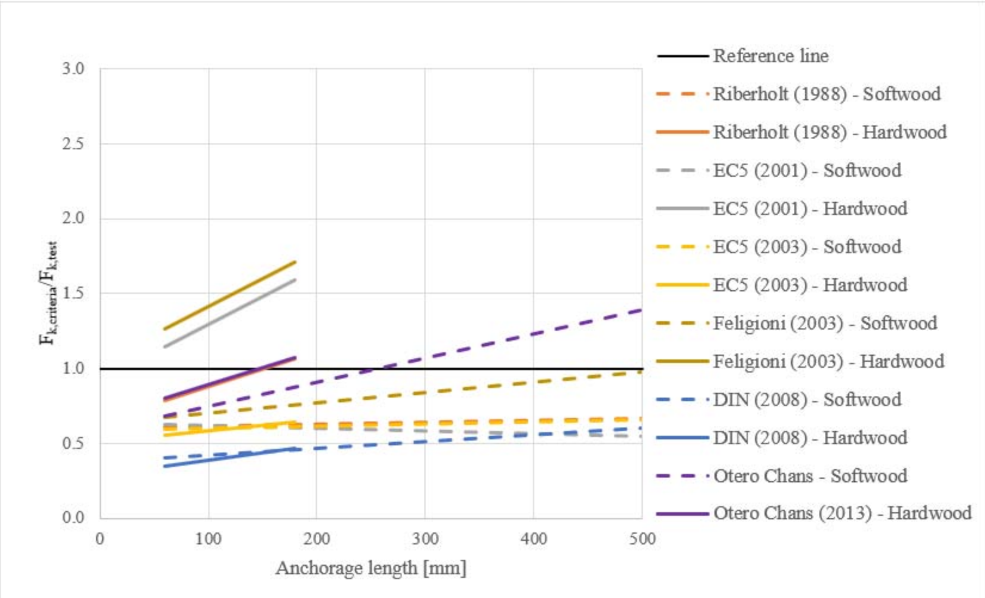

Figure 6.5. Plots showing the linear approximation of the scatter points in Figure 6.3. — test specimens with hardwood, - - - test specimens with hardwood

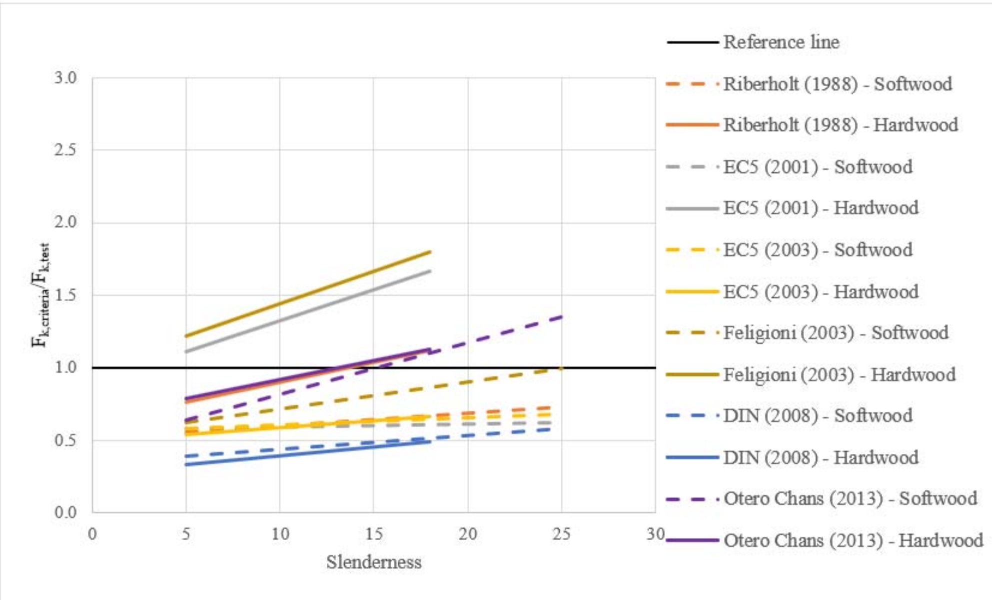

Figure 6.6. Plots showing the linear approximation of the scatter points in Figure 6.4.. — test specimens with hardwood, - - - test specimens with hardwood

7 Discussion

In this chapter the results of the previous chapter are discussed and interpreted. Each design equation is evaluated as well as the difference between hardwood and softwood.

7.1 Discussion of results

When studying Figure 6.1, it can be stated that higher anchorage length gives increased capacity, both for hardwood and for softwood specimens. Furthermore, it appears from Figure 6.1 that the softwood samples had much higher capacity. A possible explanation is that the test specimens with longer anchoring lengths had a larger diameter of the rod, which results in an increased capacity. The diameter of the rod for the softwood specimens varied between 12 and 24 mm, while for the hardwood specimens the variation was between 10 and 12 mm. The diameters are thus in some cases twice as large for softwood than hardwood and the increased capacity it entails is clearly visible. So, it is also wrong to assume that connections with softwood timber gives higher capacity, something that is proven when studying the scatter points from Otero Chans (2013). In that study, tests on specimens made with both softwood and hardwood diameters were made with identical test set up including the diameter of the rod, and the result was that the hardwood test specimens had a higher capacity. Figure 6.2 shows instead the capacity plotted against the slenderness parameter, which also takes the diameter of the rod into consideration, resulting in less scatter.

The scatter plots in Figures 6.3 and 6.4 have the direct opposite appearance compared to Figures 6.1 and 6.2, with the scatter points for hardwood above the ones from for softwood, for the design equations from EC5 (2001), Feligioni (2003) and Riberholt (1988). This is because these three design equations consider the density of the timber as a parameter, and the density is much higher for the specimens with hardwood timber than those with softwood. This gives an increased theoretical capacity for hardwood specimens that is significantly higher than the capacity of the tests. The design equation from Otero Chans (2013) also contains the density of the wood as a parameter, but correction factors have been developed for possible application on both softwood and hardwood. The result can be seen in the diagrams, where the difference between softwood and hardwood is considerably smaller. The design equations from DIN (2008) and EC5 (2003) do not consider the density of the timber as a parameter and there is less difference between the scatter points for hardwood and softwood. Furthermore, there are few measurement points for anchoring lengths above 300 mm and slenderness higher than 18. So, when comparing the correlation between the design equations and the tests, it may be reasonable to ignore the anchor lengths and slenderness above those values. However, they were still retained in the plots because of their validity.

The scatter plots for the design equations from EC5 (2001) and Feligioni (2003) are very similar, which could be expected since they are based on the same previous equation. These equations are not suitable for hardwood timber since most of the scatter points are above the reference line. The same is true for softwood, even if there are only a few points above the reference line. Furthermore, the scatter is large, which in addition to the scatter points in Figures 6.3 and 6.4 also can be seen by the relatively steep slope for these equations in Figure 6.5 and 6.6. This is negative as it indicates unreliable results. However, it should be noted that Feligioni’s equation partially was derived from tests with specimens with a similar timber density as the softwood timber, and the result is much better for softwood.

The results for Riberholt's equation is similar to EC5 (2001) and Feligioni (2003), with most points for hardwood above the reference line. For softwood, on the other hand, the capacity is underestimated, and although the scatter is smaller than for EC5 and Feligioni, which is visible through a flatter slope in Figure 6.5 and 6.6.the others, this equation does not provide a reliable result and is therefore also discard.

The results from the design equation from Otero Chans (2013) are scattered around the reference line, with the majority below, for both hardwood and softwood timber. However, the cases of overestimation of the capacity and large scattering indicates that that the design equation is not reliable. Nevertheless, it is promising with the similarity between the results for hardwood and softwood, since it is preferable with an equation that can be applied to different types of wood. Therefore, the conclusion is that this proposal has great potential but should be reviewed to give more conservative results.

The scatter points for the design equations from DIN (2008) and Eurocode 5 (2003) are all below the reference line. Which means that they underestimate the pull-out capabilities in all cases and it is thus possible to apply these proposals to different types of timber. The results for EC5 (2003) are closer to the reference line, evident in Figure 6.5 and 6.6, and implicates a more efficient design. However, the scattering is smaller for DIN (2008), which implies a better inclusion of the effect of different parameters, and the efficiency can be increased with a regulation of the bond line strength parameter.

8 Conclusions

8.1 Evaluation of design proposals

When it comes to estimating the capacity of GiR connections with design equations, it is very important to have a conservative approach, as an overestimation of the capacity can lead to failure which can have major consequences for the structure. Furthermore, it was also of great interest with an equation that can be applied to different types of timber. With that in mind, the following conclusion were made:

- The theoretical capacity for hardwood specimens was significantly higher than the capacity of the tests for the design equations from EC5 (2001), Feligioni (2003) and Riberholt (1988). This was because the formulas contain the density of the timber as a parameter, and the hardwood specimens had higher density.

- The design equation from Otero Chans (2013) also contains the density of the timber as a parameter, but with correction factors for a possible broader application on both softwood and hardwood. However, the design equation should be reviewed to give a more conservative result.

- The proposals from EC5 (2003) and DIN (2008) gave the best results, even though they underestimated the capacity of the tests. EC5 (2003) was slightly more effective, but the results from the equation from DIN (2008) showed less scatter and it is therefore concluded to be the most reliable design equation of those studied in this work. However, it might need to be reviewed for increased efficiency.

8.2 Future research

The focus of this thesis has been on GiR connections with a single rod and it would be interesting to do a similar comparison of design equations for GIR connections with multiple rods. Furthermore, it had also been useful to study:

- different service classes and moisture content,
- GiR joints with composite rods,
- GiR joints with different types of adhesives,
- GiR joints with different loading, e.g. shear, bending, dynamic loading and fatigue, and
- GiR with different engineering wood products, e.g. LVL and CLT

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