THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Civil and Environmental Engineering

Development of connections for fibre reinforced bridge elements and an analysis of sustainability

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Cover:
Experimental investigation of a panel-level connection for FRP bridge decks and double-lap shear joints with steel inserts

Chalmers reproservice
Gothenburg, Sweden, 2015

Dedicated to the memory of my father, Albert

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ABSTRACT

The deterioration of existing bridge structures due to a number of causes has led researchers to pursue new construction materials with high performance, such as fibre reinforced polymer (FRP) composite materials. The inherent properties of FRP materials are their light weight, high strength and high resistance to aggressive environments. Thanks to their light weight and the potential for prefabrication, the use of FRP bridge elements brings the benefits of industrial bridge construction and swift on-site assembly, resulting in the minimisation of traffic disruption. The application of FRP members in bridges started in the early 1990s and there remains a need for research in various technical areas. To map out these areas and specify the current level of knowledge, a literature review focusing on FRP bridge decks was carried out. This resulted in the identification of a number of research needs and two of them were pursued for research in this thesis.

The first was to determine the potential of bridges with FRP bridge decks with respect to sustainability. Life-cycle cost analyses and life-cycle assessments in terms of carbon emissions were carried out on an existing steel-concrete bridge with a deck that had deteriorated where two scenarios were compared: the total replacement of the bridge with a new steel-concrete bridge and the replacement of the concrete deck with an FRP deck. The analyses revealed that the latter scenario contributes to potential cost savings and a reduced environmental impact in terms of carbon emissions over the life cycle of the bridge.

The second identified research need was the development of integral connections and joints which enable rapid on-site assembly. Firstly, an innovative panel-level connection was developed by following an approach in which the bridge owner, designer, manufacturer and contractor were all involved. Numerical and experimental work was carried out to investigate the overall structural behaviour of the developed connection. The results showed that the proposed connection has good potential to be used for FRP decks, but more experimental tests encompassing specimens with a higher level of precision are required. In addition, a detailed study of bolted joints with the aim of obtaining non-slip joints, when clearance is present, in the service state of bridges was carried out. The utilisation of steel inserts and pretensioned bolts was investigated numerically and experimentally. The results indicated that it is possible to benefit from the bolt tension and rely on the load being transferred by friction if steel inserts are used. Bolt-tension-relaxation issues are reduced by using inserts and joint efficiency can be increased.

Key words: bridge, bolt, connection, deck, fibre reinforced polymer, FRP, joint, insert, LCC, LCA

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text.

I. Mara, V. and Haghani, R. (2015), "Review of FRP decks: structural and in-service performance", *Proceedings of the ICE – Bridge Engineering*. DOI: 10.1680/bren.14.00009.

II. Mara, V., Haghani, R. and Harryson, P. (2014), "Bridge decks of fibre reinforced polymer (FRP): A sustainable solution", *Construction & Building Materials*. **50**(0): p. 190-199. DOI: 10.1016/j.conbuildmat.2013.09.036.

III. Mara, V., Kliger, R. (2015), "An approach to the development of connections between FRP bridge decks", submitted for publication to *Case Studies in Structural Engineering*.

IV. Mara, V., Al-Emrani, M. and Haghani, R. (2014), "A novel connection for fibre reinforced polymer bridge decks: Conceptual design and experimental investigation", *Composite Structures*. **117**(0): p. 83-97. DOI: 10.1016/j.compstruct.2014.06.020.

V. Mara, V., Haghani, R. and Al-Emrani, M. (2015), "Improving the performance of bolted joints in composite structures using metal inserts", submitted for publication to *Journal of Composite Materials*.

THE AUTHOR’S CONTRIBUTIONS TO THE APPENDED PAPERS

The contributions of the author of this thesis to the appended papers are described below.

I. Responsible for the planning, conducting the literature review and writing the paper. The co-author provided comments.

II. Responsible for planning and writing the paper. Conducted the literature study and the life-cycle analyses. The co-authors provided comments and minor revisions.

III. Responsible for the development of the approach, planning and writing the paper. Co-ordinated the interaction between the involved parties in the evaluation of the connection concepts. The co-author provided comments.

IV. Responsible for the numerical modelling, development of the test set-up, executing the experimental tests and the evaluation of the test results. Planned and co-ordinated the writing of the paper. The co-authors provided comments. Shared responsibility with the co-authors for the conceptual design of the presented connection.

V. Responsible for the numerical modelling, development of the test set-up, planning and executing the experimental tests and the evaluation of the test results. Planned and co-ordinated the writing of the paper. The co-authors supported the technical content and outcome of the paper.

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Conference proceedings

Mara, V., Al-Emrani, M., Kliger, R. "Upgrading of an Existing Concrete-Steel Bridge Using Fibre Reinforced Polymer Deck – A Feasibility Study" at the *1st FRP Bridges Conference*, September, 2012, London, UK

Mara, V. and Haghani, R. "Upgrading Bridges with Fibre Reinforced Polymer Decks – A Sustainable Solution" at the *CECOM Conference*, November, 2012, Krakow, Poland

Mara, V., Haghani, R., Sagemo, A., Storck, L. and Nilsson, D. "Comparative study of different bridge concepts based on life-cycle cost analyses and life-cycle assessment", at the *Asia-Pacific Conference on FRP in Structures* (*APFIS 2013)*, December, 2013, Melbourne, Australia

Mara, V. "Experimental investigation of bolted connections with inserts for FRP structural members" at the *International Conference on Advances in Composite Materials and Structures,* April, 2015, Istanbul, Turkey

Licentiate thesis

Mara, V. "Fibre reinforced polymer bridge decks: Sustainability and a novel panel-level connection". Licentiate Thesis. Lic 2014:1. Department of Civil and Environmental Engineering, Chalmers University of Technology, 2014, Sweden

Miscellaneous

Mara, V., Poneta, P., Pasquale, A., Hermillosa, C., and Wlasak, L. D4.18 "Techniques of off-site fabrication and on-site assembly of new bridges", PANTURA, Work package 4, Task 4.2, December, 2013

Mathern, A., Mara, V., Quinchia, J. P., Poneta, P., and Hermillosa, C. D4.19 "Flexible assembly methods", PANTURA, Work package 4, Task 4.3, December, 2013

Contents

Preface

This thesis presents the results of research carried out at the Division of Structural Engineering, Steel and Timber Structures, Civil and Environmental Engineering Department, from August 2011 to August 2015. The research covers a study of fibre reinforced polymer bridge decks, the sustainability of using FRP materials in bridges and connections and joints between FRP elements.

Part of this thesis was associated with the European project, PANTURA no. 265172, which was co-financed by the European Commission FP7-ENV-2010. I would therefore like to express my gratitude to all the partners in PANTURA for their great collaboration.

I would like to thank my examiner, Professor Robert Kliger, my supervisor, Associate Professor Mohammad Al-Emrani, and my co-supervisor, Associate Professor Reza Haghani, for their guidance, enthusiasm and technical knowledge. Our brainstorming sessions brought about the realisation of this thesis. I must also extend my thanks to the technical staff at Chalmers, Lars Wahlström and Sebastian Almfeldt, for their help in executing the experimental tests. Special thanks also go to Jeanette Kliger for language-editing this thesis and the appended papers.

I would like to express my appreciation to all my colleagues and many dear friends, all of whose names are impossible to mention here, for providing constant support, joyful moments, inspiration and laughter.

A great many thanks goes to my boyfriend, Sjouke, for his love, encouragement and the colours he has brought to my life. Our discussions on the topic of sustainability have certainly helped when reflecting on my own research.

Finally, I would like to thank my mother and my brother whose unconditional love and support will be forever appreciated.

Valbona Mara

Göteborg, 2015

1 Introduction

1.1 Background

A major concern when it comes to reinforced concrete bridge superstructures is the reduction in service life and durability due to corrosion, especially in cold areas where de-icing salt is used. The corrosion of steel reinforcements, induced by chloride ion ingress into concrete from de-icing salts, is categorised as one of the main causes of reinforced concrete deterioration [1, 2]. This deterioration eventually causes enough damage to warrant a superstructure replacement or the rehabilitation of bridges, resulting in large-scale economic implications. The replacement and rehabilitation of existing bridges is also required in many cases to meet the current need for higher traffic loads and volumes. This growing need for infrastructure development results in increased demands in terms of performance and costs. The cost of bringing the deficient bridges to an acceptable level is usually high. Today, when planning bridge-related construction projects, one main priority which is assigned by transport administration authorities is the minimisation of traffic disruptions because of the potential economic and safety impact [3]. This is particularly important in densely populated areas, in which bridge construction processes must accommodate adverse social, environmental and economic impact, including traffic disruption, noise pollution, inefficient use of resources, user safety, user delay costs and the like.

These issues have increased our awareness of the necessity to provide solutions for the new construction and renovation of bridges, with the aim of increasing durability, to reduce on-site activity and traffic disruption and to provide cost efficiency.

Fibre reinforced polymer (FRP) composite material has been found to be attractive as a solution in the past two decades. In addition to its corrosion resistance, the material exhibits numerous beneficial properties, such as light weight, high specific stiffness and strength and high fatigue properties. Fibre reinforced polymer materials lend themselves very well to industrial construction because of their prefabrication potential and low self-weight. For bridges, the advantages that can be expected from an industrial construction process are numerous; they include accelerated bridge construction, improved constructability, reduced adverse social impact, increased safety and improved environmental impact (see, for example, [4, 5]). These advantages have been demonstrated in many FRP bridge projects [6-10].

However, the application of FRP materials in bridges might seem unattractive due to their higher initial cost compared with conventional materials. By considering only the initial costs, the advantages of FRP materials could easily be overlooked. In reality, there are costs beyond the initial costs that should be considered in the cost estimation of bridges. Life-cycle cost (LCC) analyses, which add up the total life-cycle costs, including all costs from acquisition to demolition, are an evaluation method to assess the economic viability of bridges. In addition, the environmental impact of bridges from a life-cycle perspective has attracted a great deal of attention from bridge authorities due to the current extensive resource consumption. It is therefore of interest to study the cost efficiency and environmental impact of bridges utilising FRP materials compared with conventional bridge design.

Fibre reinforced polymer material is regarded as a relatively new construction material and there are many areas to be explored. One such area is the development of connections – often the most critical part of a structure – between the FRP structural members. The design of connections represents one of the greatest challenges in the design of structures and it becomes even more critical in the case of fibre reinforced polymer structures due to the complexities involved in material orthotropy, the lack of material plasticity and geometric effects, for example. The connections in existing FRP bridges are usually over-designed. It is often the case that hybrid joints, a combination of bolted and adhesively bonded joints, are used to obtain redundant connections with the capacity to support the load from each joint type, as implemented in bridges described in [11, 12]. This is often done as a result of the low level of confidence in adhesive bonding in infrastructure applications. However, the over-design of joints results in increased costs, non-optimised structures and low design efficiencies. In addition, the current trends are moving towards an increasing demand to deliver joints that provide rapid on-site assembly. As a result, practical, economically feasible solutions need to be developed in order to ensure structurally efficient connections and swift on-site assembly.

1.2 Aim and objectives

The aim of this thesis was to explore the application of FRP materials in bridges, to analyse their economic and environmental feasibility and to develop connection solutions that facilitate the application of these materials. Within this overall aim, some specific objectives were determined.

1) To review and evaluate the structural and in-service performance of FRP decks and connections at different bridge levels and to determine possible knowledge gaps

2) To investigate the cost-effectiveness and the environmental implications of using FRP decks in bridge rehabilitation projects

3) To develop a panel-level connection for FRP decks, which enables swift on-site assembly, through a multidisciplinary, integrated planning approach between the bridge owner, manufacturer, contractor and designer. Experimentally and numerically to assess the structural performance of the connection

4) To review the structural performance of different types of joint used for FRP elements, focusing mostly on bolted joints

5) To develop mechanical joints applicable to FRP bridge elements, which are slip resistant in the serviceability limit state and enable swift, on-site assembly and disassembly and to assess their static performance

1.3 Organisation and research methodology

The main research methods followed in this thesis to fulfil the objectives were literature reviews, numerical analyses, experimental tests and life-cycle approaches. An overview of the organisation of the study, along with the principal research methods, the respective objectives (introduced in Section 1.2) and the respective papers (Papers I-V), is shown in Figure 1.1.

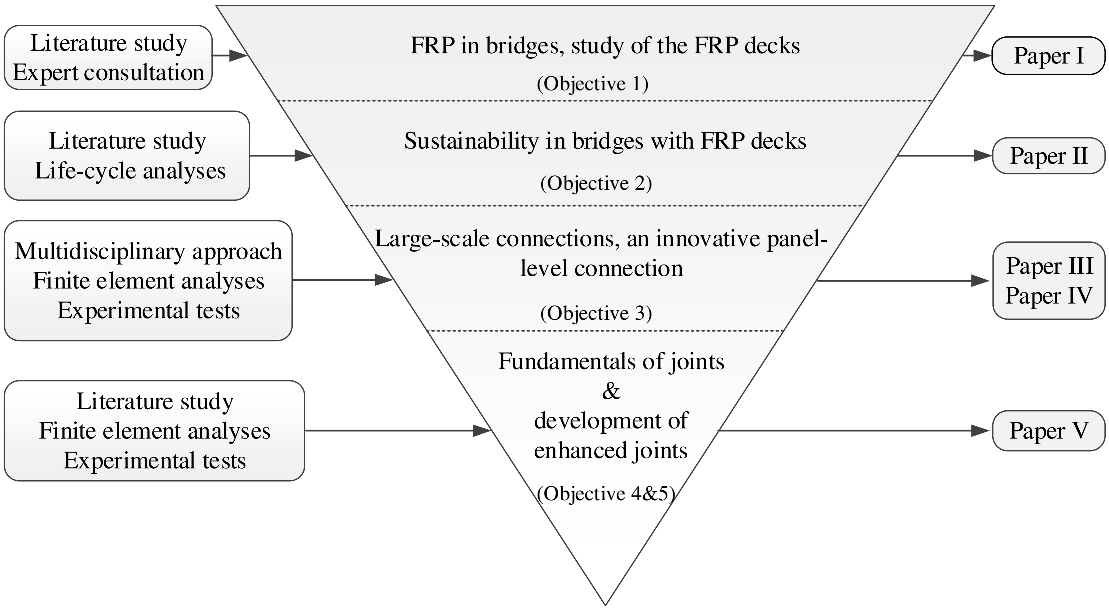


Figure 1.1 Organisation and research methodology of this thesis and the respective papers

As illustrated in Figure 1.1, the study started broadly by investigating the application of fibre reinforced polymer materials in bridges, after which it was narrowed to the topic of joints.

Firstly, the application of fibre reinforced polymers in bridges, focusing on FRP bridge decks, was studied. The latest research and practice were synthesised and several experts and practitioners were consulted in order to characterise the structural behaviour and field performance of FRP decks and connection details between bridge elements. This led to the identification of necessary further research and formed the motivation for the studies of sustainability and connections in this thesis.

The aspects of sustainability and their association with bridges using FRP materials, related to Objective 2 as shown in Figure 1.1, were identified by evaluating and characterising the existing literature on this topic. A comparative analysis utilising the approaches of life-cycle cost (LCC) analysis and life-cycle assessment (LCA) was conducted to study whether the use of FRP bridge decks contributes to a more sustainable bridge construction. An existing steel-concrete bridge with a concrete deck that had deteriorated was selected to serve as a case study. Two scenarios were examined: the total replacement of the bridge and a bridge rehabilitation scenario in which the concrete deck was replaced by an FRP deck. Initially, the efficiency of FRP decks for upgrading the case-study bridge was examined in a finite element study. The LCC and LCA analyses were carried out using Excel-based software developed by the author for the purpose of this study. This study resulted in the production of Paper II.

As shown in Figure 1.1, the study in this thesis proceeded with the topic of large-scale connections, which is related to Objective 3. An innovative panel-level connection for FRP bridge decks was developed. This development started with a conceptual design. In the conceptual design, an approach in which the bridge client/customer, the designer, the manufacturer and the contractor were involved was followed. This approach, which was inspired by and based on the idea of the quality function deployment tool found in the literature, included the establishment of matrices in order to map out the requirements originating from the involved parties and to evaluate different connection concepts. The evaluation of the different connection concepts led to the winning connection concept, which is the innovative panel-level connection presented in this thesis. The approach to the development of this connection is described in Paper III. The finite element method was subsequently used initially to design and examine the overall structural behaviour of the panel-level connection. The ABAQUS 6-11.3 commercial software was used for the analyses. Experimental tests were performed to verify the design and study the performance and the load-carrying capacity of the connection. The experimental tests included only static bending tests and can be found in Paper IV.

The research proceeded to the fundamentals of the joining techniques for composite structures with the emphasis on bolted joints, which is related to Objective 4 of this thesis. The characteristics and basic principles of the different joining techniques used for composite structures were reviewed in the existing literature and they are presented in Chapter 4 of this thesis. The parameters affecting joint performance were identified and discussed. This review helped to acquire an in-depth understanding of joint performances and to outline research needs. Addressing the research needs, bolted joints with steel inserts were developed. This study is related to Objective 5 in this thesis. An experimental programme was initiated to quantify the short-term composite material properties, to evaluate the behaviour and performance of the designed bolted joints with inserts and to quantify the long-term bolt-tension relaxation. Available standard test methods were applied in this work to quantify the material properties, such as tensile, compressive, in-plane shear and bearing. Single-bolted, double-lap joints were loaded in static shear to characterise the behaviour of the developed bolted joints with inserts. Long-term bolt-tension-relaxation tests were conducted to quantify and compare the relaxation of the bolt pre-tension in bolted joints with and without inserts. The tests were conducted at room temperature in dry conditions for 29 days. The bolt tension was controlled and monitored through strain gauges instrumented in the bolts. To deepen the understanding of all the load mechanisms and promote a more meaningful interpretation of the experimental results, finite element analyses were utilised. The material properties obtained through the experimental standard test methods were used as input data in the finite element analyses. The finite element method was only used to study the short-term static performance of the joint tests. The long-term bolt-tension relaxation was not studied using the finite element method. As shown in Figure 1.1, this entire study resulted in the realisation of Paper V.

1.4 Scope and limitations

Fibre reinforced polymer (FRP) material is a combination of polymer resins with stiff and strong fibres such as glass, carbon, aramid or basalt fibres. This thesis covers the fibre reinforced polymer materials that are composed of glass fibres. In this thesis, the designation FRP thus refers to glass fibre reinforced polymers (GFRP).

The application of FRP materials can involve pedestrian or road bridges. In this thesis, interest has focused on the application of FRP decks in road bridges. A review of the FRP decks was presented in Paper I. The scope of this review was limited to the static and fatigue performance of these decks and dynamic performance and durability issues were not discussed.

In Paper II, the sustainability aspects, social, environmental and economic, were discussed. The social aspects were not covered in detail, but they were limited to the ones included in the European project, PANTURA within the 7th Framework Programme. Furthermore, the life-cycle assessment was solely limited to an evaluation of the carbon emissions in the case-study bridge.

A review of the various types of joint between FRP elements is provided and discussed in Chapter 4. Interest focused primarily on bolted joints. This review was limited to the static behaviour of joints, including the effect of various parameters. In addition, it was restricted to single- or double-lap, plate-to-plate joints loaded in shear. Multi-bolted, frame and moment-resistant joints are outside the scope of this thesis.

The experimental programme of the joint tests, described in Chapter 5 and Paper V, was limited to single-bolted, plate-to-plate FRP joints with a double-lap shear configuration and in-plane static loading. The material was composed of glass fibre reinforced polymer (GFRP) and the results of the tests might therefore not be applicable to other types of material. The experiments were carried out in lab conditions and any environmental effect was not investigated. Any possible size effect was not investigated.

1.5 Research significance

The driving forces for the research, development and application of fibre reinforced polymer structures are their inherent properties, such as light weight, corrosion resistance, high strength, easy application and minimum maintenance. As the application of FRP materials in bridges becomes more widespread, there is a need to fill the gaps in knowledge relating to the structural performance, technical requirements and practical issues.

In this thesis, a systematic review of existing research efforts and achievements relating to FRP decks regarding their structural and in-service performance is provided (Paper I). This review demarcates research frontiers and identifies areas of future research, which is beneficial to the research community.

The implications of using FRP materials in bridges are of great importance from a sustainability point of view, as bridge authorities are continuously struggling to include sustainability principles in the design of bridges. The corresponding work is less frequently found in the literature and more studies are therefore required to increase our knowledge in this area. This issue was addressed in this thesis by discussing whether the use of FRP decks contributes to sustainable development, taking account of the three pillars of sustainability: social, environmental and economic. The environmental and economic aspects were taken further and evaluated in a case-study bridge (Paper II). It is to be hoped that this study will increase awareness and knowledge of the sustainability implications of using FRP decks for bridge projects.

Connections are often the weakest links in structures. A limited amount of research is devoted to connections in FRP structures in the field of civil engineering. More work in this research field is therefore needed to develop appropriate connections, assess their performance and develop and refine design methods for these connections. The FRP deck panel-level connection and the bolted joint with inserts developed in this thesis feature several unique contributions to the scientific community.

The panel-level connection concept for FRP decks is an innovative concept and presents several advantages: (i) it avoids the need to execute bonding operations on the construction site; (ii) it allows for more rapid installation; and (iii) it makes the disassembly of bridge panels possible (Papers III and IV).

The study of the developed bolted joint with inserts helped to: i) strengthen previous research results, ii) increase our understanding of the performance of these joints and iii) make possible the reduction of long-term bolt tension relaxation (when bolts are pretensioned), by utilising steel inserts, which, to the author’s knowledge, has not been studied previously. Reducing the bolt tension relaxation leads to the exploitation of the bolt tension and taking advantage of force transfer by friction in bolted joints. In this way, slip-free bolted joints in the serviceability limit state of bridges can be obtained. Furthermore, the change in the bolt tension during the static loading of the joints was monitored in the conducted tests in this thesis; in the existing literature, this parameter is usually missing in joint tests with pretensioned bolts. This provided a deeper understanding of the change in bolt tension during the static loading of the joints. The results of this study also open the door to further investigations of these joint types (Paper V).

1.6 Thesis outline

This thesis consists of six chapters and five appended papers, denoted as Paper I-V. The chapters serve as an introduction or a supplement to the work presented in the appended papers. Throughout the chapters, reference is therefore often made to the papers.

Chapter 2 briefly introduces the application of fibre reinforced polymer materials in bridges, with the emphasis on FRP decks. The types and manufacturing methods of FRP decks are given. This chapter primarily refers to Objective 1 and makes reference to Paper I that deals with a detailed review of the structural and field performance of FRP decks. A summary of this review is given in this chapter.

Chapter 3 highlights the importance of sustainability and a life-cycle, holistic approach to bridge applications. A life-cycle cost analysis and a life-cycle assessment are conducted on a case study, which are described in more detail in Paper II. The key findings of this case study are provided. In addition, Chapter 3 introduces an innovative concept for panel-level connections for FRP decks. The development process of the connection from conceptual design to verification through testing is described in Paper III and Paper IV. The key findings of these papers are highlighted. This chapter relates to Objectives 2 and 3 and Papers II, III and IV.

In Chapter 4, a review of the joining techniques for FRP elements and their performance is presented. In particular, the parameters affecting the performance of these joints are discussed. The chapter concludes with a summary of these joints. This chapter is associated with Objective 4.

Chapter 5 deals with material characterisation tests, experimental tests and numerical analyses of bolted and bonded joints. This chapter is a complement to Paper V and it is related to Objective 5. This chapter concludes with a summary of the experimental and numerical findings.

The thesis ends with general conclusions and suggestions for further research in Chapter 6.

2 Fibre reinforced polymer materials in bridges

2.1 Applications

FRP composites have been used as a construction material for several decades. It is widely recognised that the world's first FRP vehicular bridge is Miyun Bridge, built in 1982, in Beijing [13]. Since then, the advances in FRP composite products have led to the production of structural bridge systems that allow for the rapid deployment of bridges using modular system concepts.

All-FRP bridge members have been predominantly used as superstructural elements, such as decks, beams, cables or tendons. The world's first highway bridge using FRP composite reinforcing tendons was built in Germany, in 1986. FRP decks have been mostly utilised to rehabilitate or to increase the load-carrying capacity of existing bridges. Their use in new bridge structures has been less widespread. In 1996, the first FRP vehicular bridge deck was installed in Russell, Kansas. Since then, more than 100 FRP composite bridge decks have been installed in the USA and around the world and most of them are still in service [7]. FRP girders have been used for the construction of new bridges [14, 15], but their application has been less common compared with FRP decks. They are made of glass FRP, carbon FRP or a hybrid of the two. FRP decks or girders are generally combined with traditional materials such as an FRP deck on steel or concrete girders and a concrete or timber decks on FRP girders (see, for example, [16]). All-FRP bridges have been constructed as well, but they are more common as pedestrian bridges.

The substructures of the constructed composite bridges have generally been conventional reinforced concrete substructures. Hybrid substructures combining FRP materials with conventional materials, such as concrete-filled FRP tubes, have also been used [17]. GangaRao [6] argues that it is possible to design piers and abutments made solely of carbon composites as double-walled cylindrical shells with a capacity of 690 to 1,035 MPa. However, these substructures might not be cost competitive.

Fibre reinforced polymers are well suited to various applications, but they have certain outstanding advantages in some specific applications, such as:

- Bascule bridges: owing to the low self-weight of the material, the use of FRP structural members in bascule bridges is very appealing. The inherent characteristics of FRP for bridges of this type have already been demonstrated in several projects [18-20]

- Culvert bridges: today, culvert bridges are designed with steel materials that have many maintenance problems due to corrosion. FRP is a very good candidate in these bridges owing to its corrosion resistance. To date, to the author's knowledge, no such bridges have been built. A preliminary study performed at Chalmers University of Technology, Sweden, has revealed the unique potential FRP culvert bridges can offer [21]

- Projects that need to accommodate an accelerated construction schedule and high durability measures

- Special occasions on which the soil conditions are poor and high loads cannot be accommodated

To date, no pedestrian or vehicular bridge with FRP structural components has been built in Sweden. The first pedestrian bridge, called Kaponjärsbro, is planned to be built in Gothenburg in 2016, see Figure 2.1. There were several reasons for choosing FRP material for this bridge; they include the ability to shape the bridge aesthetically in an innovative design, the high durability of the material against the harsh environment and the light weight of the material. The latter was of importance due to the poor conditions of the soil that is unable to withstand high loads.

Figure 2.1 The first future FRP pedestrian bridge in Gothenburg, Sweden (courtesy of Ramböll, Sweden)

When it comes to vehicular bridges, the Swedish Traffic Administration (TRV) has initiated a research and development project in collaboration with Chalmers University of Technology in order to support a pilot project for building the first FRP road bridge in 2016, in Linghem, Sweden. It is expected that the technical evaluation of the pilot project will lay the foundation for the development of a national Swedish code for FRP bridges.

2.2 Fibre reinforced polymer decks

The replacement of decks in existing bridges is one of the most prominent problems in Sweden [22]. In this regard, it was of interest to focus on the utilisation of FRP decks for replacement or new construction purposes in bridges. This section presents the types of FRP decks, their constituent materials and fabrication techniques.

The idea of using FRP materials for bridge decks was essentially a result of a research project entitled "Transfer of Composite Technology to Design and Construction of Bridges" in 1983, an initiative taken by the Federal Highway Administration (FHWA), US. Department of Transportation [23]. Since then, research efforts focused on developing fabrication methods appropriate for bridge deck applications, understanding their behaviour under simulated vehicular loads and developing details and methods with which FRP decks can be designed and constructed.

Fibre reinforced polymer decks usually consist of E-glass fibres and thermosetting resins (polyester, vinyl ester or epoxy). Glass fibres are favoured for their substantially lower cost compared with other types of fibre, such as carbon or aramid. The fibres are in the form of roving, fabric or mats. The fabrics are made by aligning fibre strands together in multi-orientations, mainly at 0°, 90°, or ± 45°, and the mats can be produced using discontinuous or continuous fibres. The typical mechanical properties of the constituent materials of FRP decks are given in Table 2.1. Epoxy resins exhibit better structural and environmental resistance than the other resins, which justifies the higher costs.

Table 2.1 Properties of E-glass fibres and resins used for FRP decks [24, 25]

Material	Tensile strength [MPa]	Tensile modulus of elasticity [GPa]	Glass-transition temperature T_g (°C)[1]	Cost (euros per kg)[2]
Fibres				
E-glass	1724-586	69-72.4	-	1.3
Resins				
Polyester	34.5-103.5	2-4.4	75-150	1
Vinyl ester	73-81	3.0-3.5	100	3.5-4
Epoxy	55-130	2.75-4.10	100-250	9

[1] The glass-transition temperature is the temperature at which the resins start to soften and lose their stiffness and strength.
[2] Reference Mostostal Warszawa S.A. (Poland), 2013

Fibre reinforced polymer decks are distinguished by their manufacturing process as pultruded and sandwich decks. Pultruded decks are usually composed of cellular sections with different configurations manufactured in a pultrusion process. The pultrusion process is described as an arrangement of fibres that are pulled through a resin bath and heated as they pass through a die to produce a section. Pultruded decks are typically aligned transversely to the beams in a bridge, as illustrated in Figure 2.2.

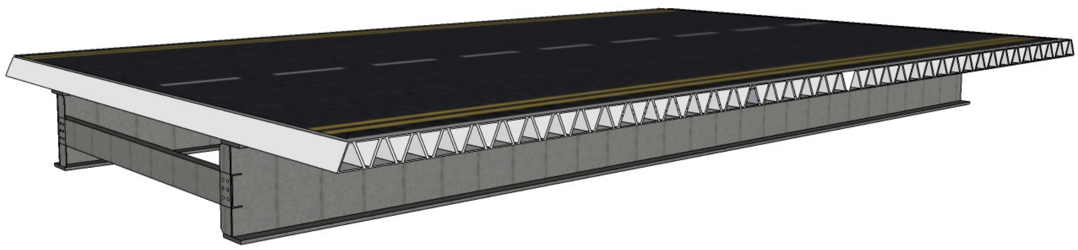


Figure 2.2 Illustration of a pultruded FRP deck on steel girders. The deck is oriented in the pultrusion direction perpendicular to the main girders

Sandwich decks have two stiff, strong face plates bonded to a core material that provides composite action to the parts. The most common forms of the core are thin-walled cellular materials (honeycomb, corrugated or sinusoidal core), stiffened foam or a combination of the two. Recently, balsa wood has been proposed by Keller *et al.* [26] as an alternative core for sandwich decks. Sandwich decks are manufactured using a resin infusion process, such as vacuum-assisted resin transfer moulding

(VARTM) or a hand lay-up process. The hand lay-up process, which is one of the oldest composite manufacturing technologies, is a labour-intensive method. Liquid resin is applied to a mould and fibre reinforcement is placed manually on top of the mould. In order to impregnate the fibre with resin and remove any trapped air, a metal-laminating roller is used. Owing to the labour-intensive work, the hand lay-up process is mostly suited for the production of components in which the production volume is low. Other limitations of this method include the low fibre-volume fraction and inconsistency in the quality of the produced parts, which significantly influence the structural properties of the parts as experienced by Camata and Shing [27]. Another concern when it comes to the hand lay-up process is the styrene emissions, which have a negative impact on the environment and the health of the workers. In the VARTM process, the reinforcement fibres are placed in an evacuated one-side mould and a top mould or else a vacuum bag is placed on the top to form a vacuum-tight seal, thus preventing toxic emissions. The resin is infused into the fibres only by vacuum and the mixture is allowed to cure under vacuum.

A comparison of the characteristics of the manufacturing techniques using the hand lay-up process as a reference is given in Table 2.2. The comparison is based on the reviewed literature, as well as consultation with manufacturing experts. The characteristics are divided into technique and produced component characteristics. When it comes to technique characteristics, pultrusion and VARTM processes are superior. The advantage of the pultrusion process over VARTM process is the high production rate. However, pultrusion process suffers to provide composite components in any geometry or size. In addition, the fibre arrangement in a component produced with pultrusion is mainly unidirectional, owing to the use of rovings. The overall quality of the produced components with the pultrusion and VARTM process are comparable and satisfactory, whereas components with lower quality are obtained by the hand lay-up method. Recently, a filament winding method has been utilised to manufacture FRP decks, but it is still at the research stage and, to the author's knowledge, decks produced with this technique have not yet been commercially produced.

An overview of the commercially available FRP deck systems for vehicular bridges is given in Table 2.3. Other FRP bridge deck types which have been installed in various bridge applications but are no longer available on the market are shown in Table 2.4.

Table 2.2 Characteristics of hand lay-up, pultrusion and VARTM manufacturing processes [28, 29]

	Hand lay-up	**Pultrusion process**	**VARTM process**
Technique characteristics			
Equipment cost	Low	High	Intermediate
Labour cost	High	Low	Intermediate
Health concerns	High	Low	Low
Production rate	Low	High	Intermediate
Produced component characteristics			
Geometry	Any	Straight, constant cross-section profiles	Any
Overall size	Any	Any length, cross-section limited	Any
Holes and inserts	Possible	Only longitudinal inserts and holes possible	Possible
Surface quality	One good surface	Good	Good
Fibre arrangement	Random or oriented mats	Rovings or oriented mats	Random or oriented mats
Typical fibre volume fractions	Up to 30%	Up to 65%	Up to 60%
Void fractions	Intermediate	Low	Low
Quality consistency	Poor	Good	Good
Mechanical properties	Poor to intermediate	Good	Good

Table 2.3 Commercially available FRP bridge deck systems

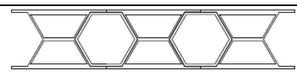
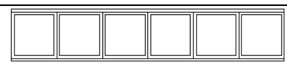
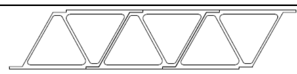
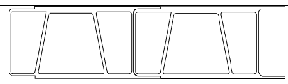
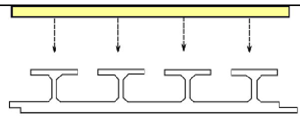
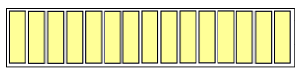
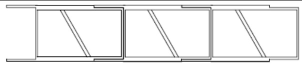
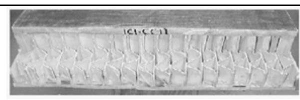
Deck system	**Manufacturing process**	**Deck height (mm)**	**Deck weight (kN/m^2)**	**Manufacturer**	**Illustration of the deck**
Superdeck	Pultrusion	203	1.1	Creative pultrusions, US	
Strongwell deck	Pultrusion	170	NA	Strongwell, US	
ASSET	Pultrusion	225	0.93	Fiberline A/S, Denmark	
Delta deck	Pultrusion	200	NA	In Korea	
ZellComp decking system	Pultrusion	Variable	Variable	ZellComp Inc., USA	
Infracore deck	Resin infusion (VARTM)	Variable	Variable	FiberCore Europe, The Netherlands	

Table 2.4 Old FRP bridge deck systems, not available in the market

Deck system	**Manufacturing process**	**Deck height (mm)**	**Deck weight (kN/m^2)**	**Manufacturer**	**Illustration of the deck**
DuraSpan	Pultrusion	195	1.05	Martin Marietta Composites, USA	
Hardcore deck	Resin infusion (VARTM)	Variable	Variable	Hardcore Composites, USA	
Kansas deck	Hand lay-up	Variable	Variable	Kansas structural composites Inc., US	

2.3 Summary

A considerable amount of research work has been devoted to FRP decks and numerous bridges have been rehabilitated or constructed using these decks. However, a review of the existing research efforts and achievements for FRP decks was previously lacking. Motivated by this, a review of the structural and in-service performance of FRP decks was conducted and is presented in Paper I. A summary of findings based on the literature study and presented in Paper I is given in the following points.

- FRP decks have been mostly utilised to rehabilitate or to increase the load-carrying capacity of existing bridges. Their use in new bridge structures has been less widespread. FRP decks weigh approximately 20% of a structurally equivalent reinforced concrete deck, making them appealing in deck replacement projects, where the reduction in dead load could produce benefits, such as an increase in live load ratings, or in deck widening projects without imposing additional loads on the substructure. The corrosion resistance of composite materials has made them particularly attractive for bridge decks, where corrosion due to de-icing salts is a matter of great concern for reinforced concrete or steel decks.

- The properties of FRP decks are orthotropic due to the material and system orthotropy. The mechanical properties and behaviour of FRP decks depend on several factors, such as the constituent materials, direction of the fibres, the method of manufacture, the cross-section geometry and the adhesives used for the deck component joints. Of these factors, cross-section geometry plays an important role in the deck properties and behaviour. Decks with triangular cross-section geometry have demonstrated higher stiffness and strength properties compared with decks with rectangular or trapezoidal configurations.

- The properties of FRP deck systems are less effective than the properties of the composite material itself, owing to the cellular nature of decks. For instance, the compression strength (transverse to the pultrusion direction) of the DuraSpan deck (see an illustration of the deck in Table 2.4) is determined as 34 MPa and it is 20% of the compression strength of the flanges of the deck which is 170 MPa. This can be attributed to the failure mode of the deck in compression, which is delamination in flange-to-web intersections due to through-thickness tensile stresses in these locations.

- Pultruded decks display mainly unidirectional load-carrying behaviour (in the direction of pultrusion) due to their unidirectional deck configuration. Sandwich decks can display bidirectional load-carrying behaviour, because they are fabricated with VARTM or a hand lay-up method which allow the shape and dimensions of the sections to be changed along the composite member.

- The common failure modes of FRP decks under static bending are delaminations in flange-to-web intersections, localised bending failure of the flanges and webs, punching failure of the deck, buckling of the flanges and webs and debonding of the core from the flanges in the case of sandwich decks. The type of patch load used in testing can affect the failure mode. If steel plates are used for the patch load, punching failure of the deck can be observed, whereas, in the case of simulated tyre loads, bending failure of the flanges and webs can take place. Differences of this kind highlight the need for standardised test methods for FRP decks.

- The ultimate failure response of FRP decks in the main load-carrying direction is usually linear elastic, with a slight non-linear envelope close to the failure loads.

- The design of FRP decks is stiffness driven. The serviceability limit state is therefore the most important criterion in the design of FRP decks. Another design criterion put forward for FRP decks in the serviceability limit state is to keep anticipated strains under 20% of the ultimate strains to avoid the risk of long-term creep rupture.

- Partial composite action can be attained between FRP decks and their supports. In capacity calculations, this composite action is not accounted for.

- FRP decks have shown satisfactory results relating to fatigue. However, additional fatigue testing of FRP decks is required to develop fatigue design methods and to test the fatigue resistance of FRP decks in various environments.

- Thermal effects can be significant in the design of FRP decks. Field observations have revealed that FRP decks can heat up rapidly when exposed to direct sunlight, causing a thermal gradient between the top and bottom surfaces of the deck. The resulting thermal stresses can be as large as stresses resulting from live loads.

- Some bridges in service have experienced cracking or debonding of the wear surface. The identified causes of cracking are local flexibility of the decks under concentrated wheel loads, poor adhesion of the wear surface to the FRP deck and mismatch of the thermal expansion coefficient or poor resistance at elevated temperature. The most commonly used wear surfaces have been polymer concrete, owing to its light weight, and asphalt. The development of appropriate wear surfaces for application to FRP decks is required.

- The main types of connection used at different levels of bridges with FRP decks are adhesive bonding, bolted connections and shear-stud connections. Problems with connections identified on site have been mostly related to inappropriate installations in the field. Inappropriate installation has been more of a typical problem for on-site bonding. Even though adhesive bonding is a suitable technique for FRP decks, it presents challenges when applied on site. In addition, it requires time for curing to develop its full strength, which jeopardises the benefit of rapid construction. Shear-stud connections have experienced serious problems of separation of the deck from the haunch on which the deck is supported, which causes impact damage to the deck, owing to the passage of vehicles. The continuous development of appropriate connections at panel and system level for FRP decks, as well as the anchorage of bridge railings, is therefore needed.

- The high initial cost of FRP decks compared with an equivalent reinforced concrete deck makes bridge authorities reluctant to select FRP decks as an option. Comparative studies of life-cycle cost and life-cycle assessment are therefore necessary for bridges with FRP decks.

- The development of FRP deck design codes is needed. The current designs are carried out by following the Eurocomp Design Code [30], which currently forms the basis of most FRP designs, national design guidelines [31-35] or specifications provided by the FRP manufacturers, which have been justified by proof tests.

3 Sustainability and a novel connection for FRP deck panels

3.1 Introduction: sustainability in bridges

The inclusion of sustainability principles in bridge construction is becoming increasingly important due to the current extensive resource consumption. While traditional design and construction focuses on performance, cost and quality principles, sustainable design and construction adds to these principles those of minimising the use of resources and the impact on the environment at every stage of use from production to disposal.

In this respect, new challenges are presented to engineers, who need to look beyond the traditional construction and consider the demands of sustainable design; i.e. seeking to achieve tailored design, construction and maintenance plans depending on the performance, environmental impact priorities, regional and social issues and economic requirements. Sustainable design constitutes three main pillars: social, environmental and economic (a description of these pillars related to bridge construction is given in Paper II). One of the main challenges when designing more sustainable bridges is correctly to estimate the social impact of bridge construction, such as current disruption, the comfort of people, work-zone safety and future benefits. This is mainly because social impact assessments tend to be qualitative rather than quantitative. Judgements made in qualitative assessments are often seen as more subjective in the construction industry, whereas the outcomes of quantitative assessments tend to be regarded as more accurate. The environmental and economic counterparts can be assessed quantitatively using life-cycle approaches, such as life-cycle assessment (LCA) and life-cycle cost (LCC) analyses [7, 36-39]. Life-cycle analyses provide an indication of the cost and environmental impact of different types of technology and are supposed to be an asset in the decision-making process. However, it is important to be aware that these studies do not provide complete decision-making support, because there are always things that are excluded or conflicting goals that cannot be resolved with these analyses.

Life-cycle approaches are useful to quantify the cost and the environmental impact of a bridge throughout its life cycle [40-43]. One point of discussion when performing these analyses is the uncertainty when it comes to understanding the impact of future developments. This is particularly relevant for bridge constructions, as the theoretical life span of a bridge can be 100 years, thereby creating mistrust in the credibility of life-cycle analyses, as reported by Ozbay *et al.* [44]. These uncertainties become even more delicate for new technologies whose long-term performance is not known. It is therefore crucial to be transparent about input data when performing life-cycle analyses. Even if uncertainties might appear to reduce the certainty of conclusions, a transparent yet less certain outcome is better than nothing. Moreover, analyses such as Monte Carlo simulations or sensitivity analyses can be included, to take account of the uncertainties or the probabilities of change in the input data. The latter can be referred to as ‘dynamic’ analyses rather than ‘static’ analyses, in which the input data are not constant but change over the years. This type of ‘dynamic’ analysis is mostly applied in LCA studies dealing with energy technologies and is described more in detail in [45].

In Sweden, the government bridge client, the Swedish Traffic Administration, has imposed a mandatory requirement for the inclusion of life-cycle cost analyses in every bridge project. In the near future, this requirement is likely to be extended to include life-cycle assessments, as the government's goal is to reduce greenhouse gas emissions by 40% by 2020. These requirements underline the importance of these analyses and a complete understanding of them. For this reason, life-cycle analyses were conducted on a case study in this thesis, which is described in the following section and Paper II.

3.2 Case study: LCC & LCA analyses

Life-cycle analyses, particularly life-cycle assessments, are rare in bridge construction, especially for bridges incorporating fibre reinforced polymer structural elements. So, using life-cycle approaches, a comparative study in a typical bridge refurbishment project was conducted on an old steel-concrete bridge, see Figure 3.1. Detailed information on the case-study bridge and the analyses can be found in Paper II.

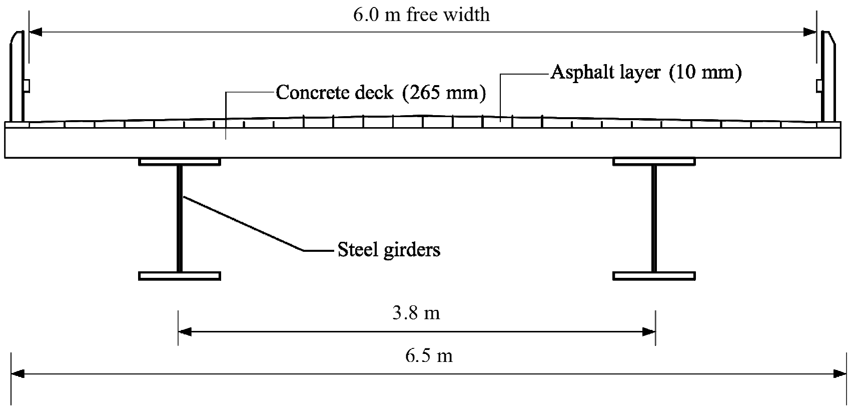


Figure 3.1 Cross-section of the old case-study bridge (Paper II)

Owing to the deterioration of the concrete deck in the old bridge, two different alternatives were considered for the refurbishment of the case-study bridge:

a) Replacement of the entire existing superstructure with a prefabricated concrete deck on steel girders

b) Replacement of the concrete deck with an FRP deck (note: replacement of the existing concrete deck with a new concrete deck was not an option due to the limited load-carrying capacity of the steel girders [46])

Initially, life-cycle inventories were made for both refurbishment alternatives in order to define the costs and the carbon emissions for each life-cycle stage of the bridge, as presented in the flow charts in Figure 3.2 and Figure 3.3.

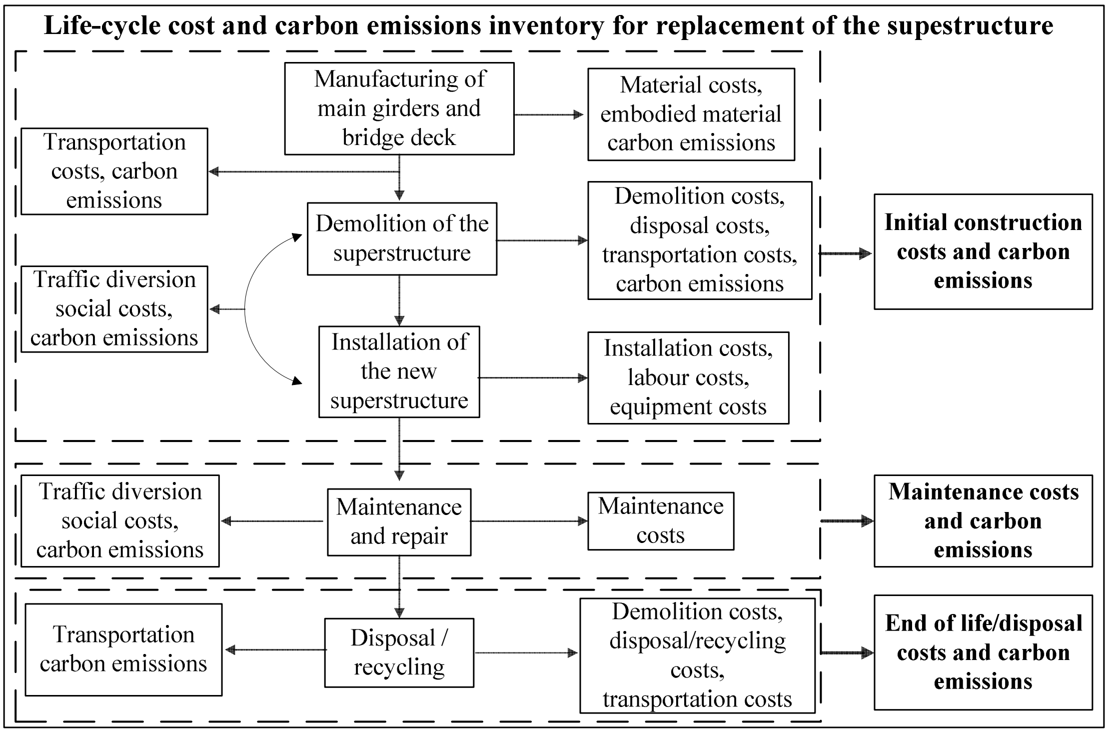


Figure 3.2 Life-cycle cost and carbon emission inventory for replacement of the existing superstructure

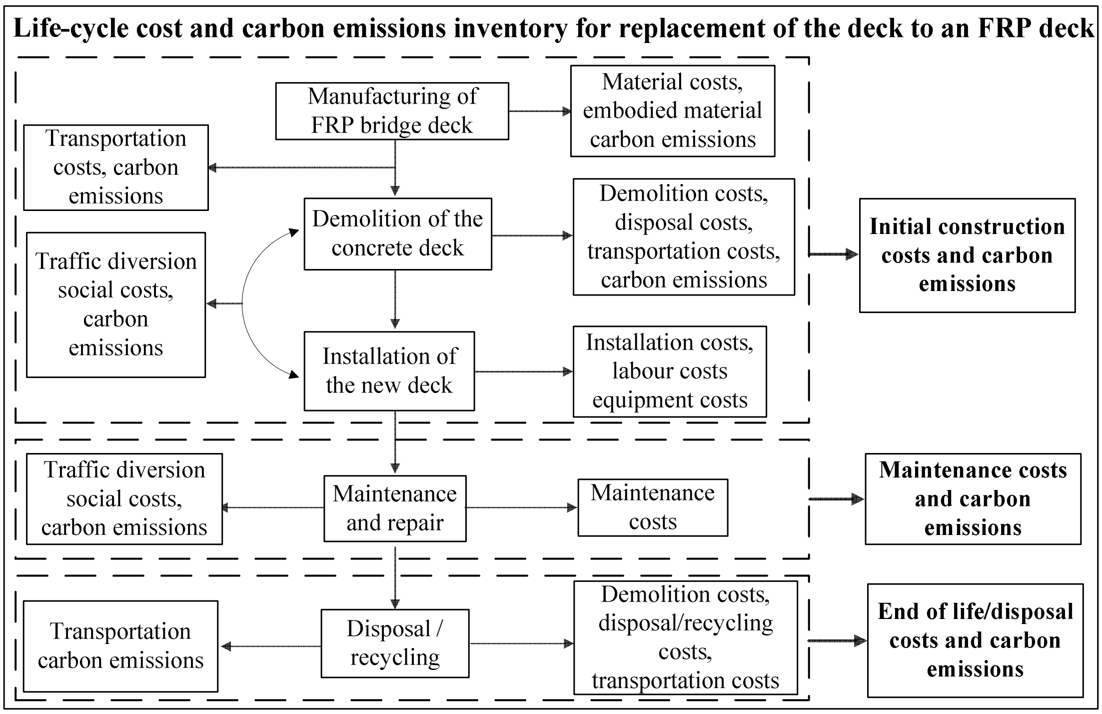


Figure 3.3 Life-cycle cost and carbon emission inventory for the replacement of the deck with an FRP deck

Based on the life-cycle inventories, life-cycle cost analyses and life-cycle assessments were performed for both alternatives. Detailed information on the input data and the analyses is given in Paper II.

The results of the total costs over the intended service life of 80 years of the bridge are presented in Figure 3.4. A breakdown of all the costs is given in Paper II.

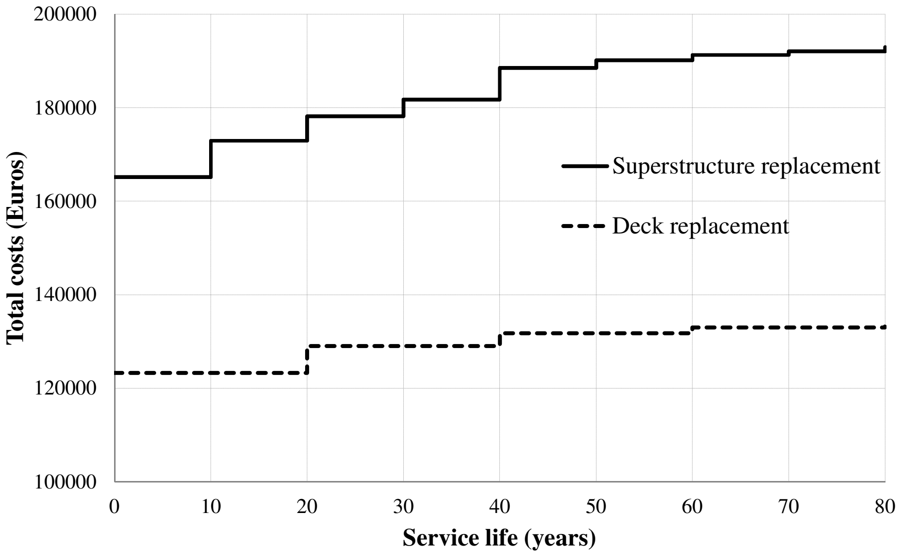


Figure 3.4 Total costs over the assumed service life of 80 years for both refurbishment alternatives

It can be noted in Figure 3.4 that the option of replacing the deck with an FRP deck results in fewer initial costs and is less costly during the entire design life, due to less maintenance work. In both cases, the initial construction costs dominate the total life-cycle costs, while the end-of-life/disposal costs are negligible, as depicted in Figure 3.5.

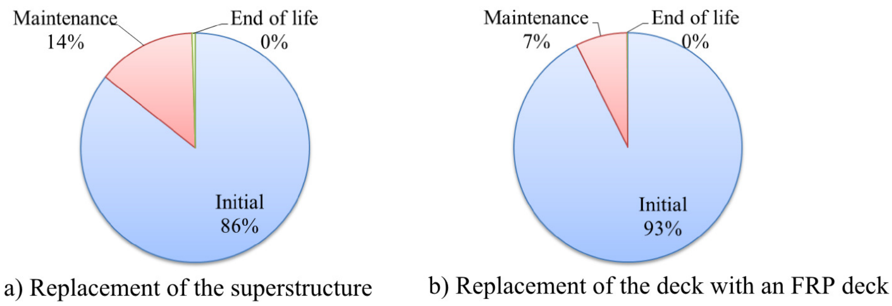


Figure 3.5 Percentage of costs from different life-cycle stages

The same results are also obtained for carbon emissions, in which the carbon emissions during the initial construction dominate, whereas the end-of-life carbon emissions are almost negligible, see Figure 3.6. In all, the results of the carbon emissions of the second alternative – replacement of the deck to an FRP deck – yield a lower value than the entire replacement of the superstructure with a new concrete-steel superstructure.

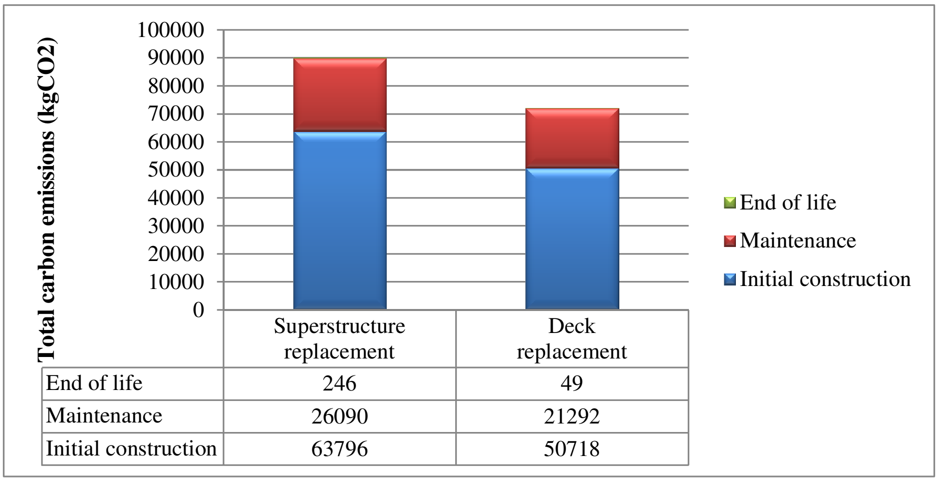


Figure 3.6 Total carbon emissions with respect to bridge life-cycle stages

3.3 Summary

The importance of sustainability to bridge applications and life-cycle analyses conducted on a case-study bridge are briefly presented in Sections 3.1 and 3.2. This study relates to Objective 2 of this thesis and Paper II. The main outcomes and reflections of this study, mainly presented in Paper II, are as follows.

- The case-study bridge analysis revealed that the replacement of the concrete deck with an FRP deck is favourable with respect to life-cycle costs and carbon emissions compared with the replacement of the superstructure with a new prefabricated concrete-steel superstructure. The total life-cycle costs and the carbon emissions are 31% and 20% respectively lower than those of the superstructure replacement alternative.

- The target bridges using FRP decks should be located on high-volume roads with complex traffic situations in order to offset the user costs and the embodied carbon emissions to an even greater degree. This was the result of a sensitivity analysis performed for the parameter of average daily traffic in Paper II.

- FRP decks can offer a sustainable solution for the rehabilitation of functionally obsolete bridges. However, life-cycle analyses are very sensitive to parameters, such as traffic diversions, transportation, materials and bridge location, and these analyses might yield different results for other rehabilitation projects.

- FRP decks offer improved social sustainability for bridges. The rapid installation of bridges incorporating FRP decks – owing to prefabrication – reduces the exposure time of workers and the travelling public to on-site work activity; thereby mitigating accidents and improving safety. In addition, the inconvenience to users, such as traffic congestion, bridge lane blockages, speed limits and air and noise pollution, is minimised.

- One challenge when performing the LCA analysis in this study was the poor availability and reliability of data, which implies some uncertainty in the final estimations. To increase the credibility of these analyses, the availability and reliability of data must be secured at national or international level. Today, efforts to improve and develop databases for input for LCA analyses are on-going.

- Additional life-cycle analyses addressing environmental impact other than carbon emissions, such as acidification potential (AP), eutrophication potential (EP), abiotic depletion potential (ADP), ozone depletion potential (ODP), ecotoxicity (ETC) and human toxicity (HTC), should be performed on other bridge cases.

3.4 An innovative panel-level connection for FRP decks

One outcome of the literature review of fibre reinforced polymer decks in Paper I was that the connection details for FRP decks require further development to ensure efficient, rapid on-site assembly. In this thesis, the emphasis was placed on panel-level connections for FRP decks. One of the common ways of connecting FRP decks on site is to use adhesively bonded connections. These connections have some shortcomings when it comes to on-site implementation and they are described in detail in Papers I and IV. One of the main shortcomings is the prolonged time over which the bridge is out of service due to the time required for curing the adhesive bond, leading to traffic disturbances. Motivated by this, an innovative panel-level connection for FRP decks, which enables rapid, straightforward on-site assembly, was developed, as illustrated in Figure 3.7. The concept is based on the mechanical interlocking of the two modules of the connection sliding into one another at an angle of 45^{o}. A tongue-and-groove mechanism is used in the connection to ensure full mechanical contact between the two modules. The difference in length of the tongues and grooves was opted for the ease of manufacturing and on-site assembly. The shape of the connection module shown in Figure 3.7 was also designed to adapt to the ASSET deck profiles, which were utilised in the experimental tests. According to this concept, the connection modules are bonded to the FRP deck panels off site and are then assembled on site.

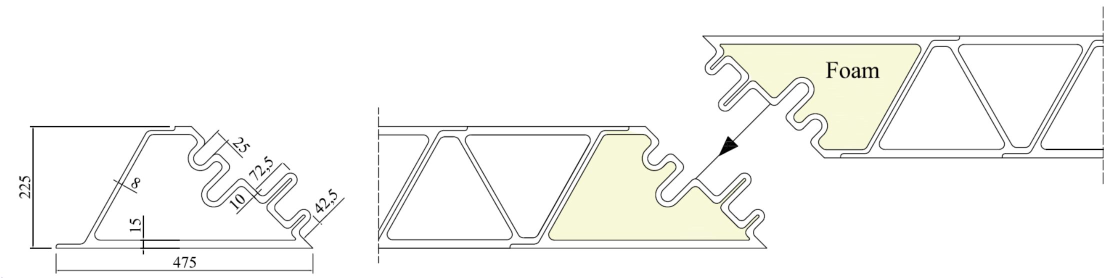


Figure 3.7 Geometry and dimensions of the connection module in mm (left) and configuration of the structural assembly (right)

The developed concept was the result of an interaction between the client, designer, contractor and manufacturer. The client in this thesis is the bridge owner. A methodology that included the aspects and demands of all the involved parties was developed for the conceptual design of the connection. The methodology is described in detail in Paper III. The connection concept was then designed in detail using the finite element method and the design was verified through experimental investigation. Experimental testing included testing of a large-scale specimen of dimensions 3 x 3 m under static bending in different load configurations. The tests were distinguished as serviceability load limit test and a final test up to 433 kN load. The detailed design and the experimental investigation of the connection are described in Paper IV. The key findings related to the connection in Paper III and IV are given in the following section.

3.5 Summary

A novel connection was proposed for fibre reinforced polymer bridge deck panels with potential for rapid on-site assembly. This study was associated with Objective 3 of the thesis and Papers III and IV. The key outcomes of Papers III and IV are as follows.

- Collaborative working can deliver innovative technology solutions. In the design of the connection, not only the primary functionality of the connection but also the productivity, buildability and serviceability were taken into account through collaborative work.

- The overall response of the connection was promising. The connection was effective with regard to rapid assembly, which translates to a substantial reduction in the total on-site construction time. The design of the connection also allows and supports thermal movements in bridge service.

- Owing to manufacturing difficulties, the final quality of the connection prototype was not totally satisfactory. This led to misfit and gaps between the connection module surfaces, which, in the serviceability limit state of bridges, can pose a threat in terms of wear-surface cracking. Deflection inconsistencies at the top flanges of the connection modules were observed in the performed experimental tests. Specimens with tight tolerances and an applied wear surface are therefore recommended for further testing.

- Pseudo-ductile behaviour could be detected in the load-displacement curve of the final experimental test loaded to 433 kN. This behaviour was a result of the local failures in the FRP deck panels which were bonded to the connection modules. Progressive local failures can give FRP structures non-linear, pseudo-ductile load-deflection behaviour, even though the material itself can be linear elastic and brittle in nature. The local failures in the FRP deck panels, in the form of delaminations at the flange-web intersections, started at a load level 50% higher than the ultimate limit state load. The ultimate limit load was considered to be 1.35 times higher than the serviceability limit load of 150 kN, which represents one wheel load. Failures in the connection modules were visible at load levels above 400 kN, in the form of crushing of the foam and separation of the bottom flange from the inclined ‘tongue-and-groove’ web.

The results indicated that the connection concept had sufficient load-carrying capacity.

- Delamination failures at the web-flange intersections in the ASSET deck resulted due to through-thickness tensile stresses in the intersections. At the load level of delamination initiation (at 315 kN), the longitudinal and transverse stresses in the flanges of the ASSET deck remained fairly low, approximately 10% of the ultimate strength. This demonstrates the sensitivity of the composite material to through-thickness tensile stresses, which control the exploitation of the material.

- Further tests are required to examine the behaviour of the connection in various static loading schedules. In addition, tests to examine the fatigue performance and the environmental effects on the durability of the connection are necessary.

4 Fundamentals of joint types in FRP members

The main joining techniques related to FRP decks are described in Paper I. This chapter aims to introduce the primary methods used to join the FRP composite structures at small-scale level and to present the fundamental mechanisms unique to each type of the joining method (related to Objective 4). The basic principles, such as safety and design requirements, are the same for all levels of joining. As a result, the information given in this section is also applicable to large-scale joining techniques. However, special attention is usually required for large-scale joints.

The main techniques for joining FRP composites are mechanical fastening via fasteners such as bolts, adhesive bonding and hybrid joints by combining fasteners and bonding or interlocking joints. Fusion bonding is another technique used for joining composites, but this method is limited to thermoplastic composites and is therefore outside the scope of this thesis. Most emphasis is placed on the bolted joints in this chapter. In this thesis, the term “joint” refers to the small-scale joints such as single- or double-lap shear joints, whereas the term “connection” refers to structural joints between members such as FRP bridge decks.

As fibre reinforced polymer composites were developed primarily in the aerospace and defence industries, a massive amount of research is being conducted on composite joints from the aerospace point of view. For instance, investigation into the use of bolted joints for composite structures began in the United States in the mid-1960s in the aerospace industry [47]. Even though the research focuses on joints that are applied in the aerospace industry, such as thin CFRP laminates rather than GFRP, it is fairly beneficial for civil engineers when it comes to understanding the fundamentals and the basic principles of composite joints. In spite of this, the research might not be directly applicable to civil engineering structures due to the differences in the geometric scales, composite material properties and loads. So, in the early 1990s, together with the introduction and use of FRP material in civil engineering structures, research on mechanical and bonded joints in composite structures began in the field of civil engineering.

4.1 Bolted joints

4.1.1 Failure modes

Mechanical joints, although easy to implement in an industrial environment, can be prone to high stress concentrations and localised damage due to the introduction of holes. The stress concentrations are more pronounced for composites compared with isotropic or plastic materials due to their anisotropic nature and lack of plasticity. In addition, holes give rise to interlaminar three-dimensional stresses, as illustrated in Figure 4.1, due to free edge effects. To suppress these interlaminar stresses, the free edges can be reinforced by some type of insert around the hole or by introducing compressive stresses. The reduction of interlaminar stresses by means of bonded inserts at the free edges was demonstrated numerically by Heyliger and Reddy [48].

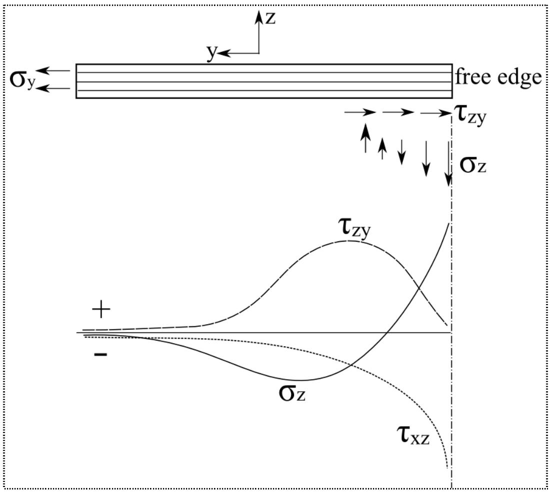


Figure 4.1 Illustration of the interlaminar stresses at the free edge of composite laminates

Even though FRP composites lack plasticity, Hart-Smith [49] observed that local debonding or delamination around the hole (not fibre breakage) can produce some relief of stress concentrations and allow local load sharing between fibres when looking at micro level, see Figure 4.2. The stress concentration relief is larger for small bolts than for large ones. It is also more pronounced for GFRP than CFRP materials with the same resin due to the lower modulus and much greater failure strain of the glass fibres [49]. These delaminations are favourable with respect to tension failures alongside the bolt hole, but they reduce the bearing load capacity. Due to these phenomena, bolted joints in fibre reinforced composites fail at loads that cannot be predicted by either perfectly elastic or fully plastic assumptions [49-51].

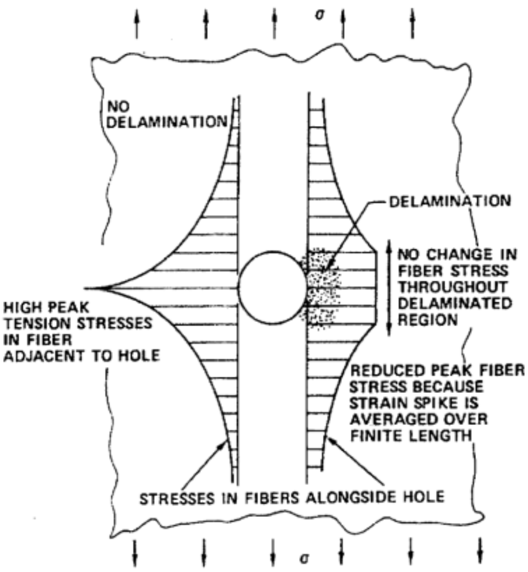


Figure 4.2 Stress concentration relief in composite bolted joints by delamination [49]

The failure modes in bolted joints, illustrated in Figure 4.3, are as follows.

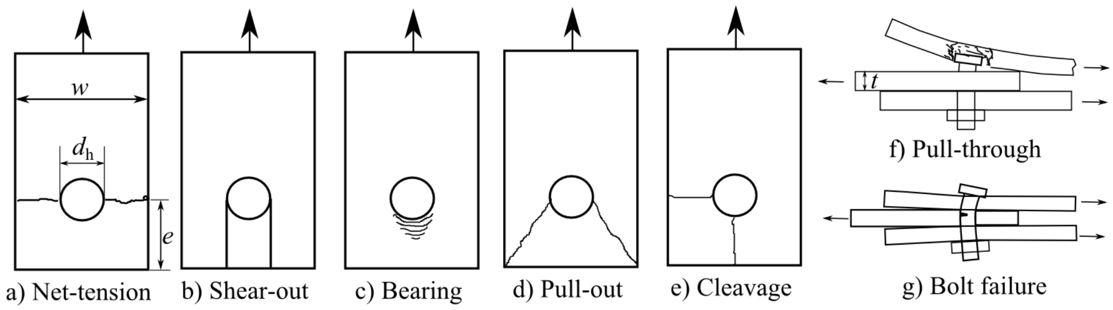


Figure 4.3 *Possible failure modes for composite plate-to-plate, single-bolted joints*

a) Net-tension failure: is caused primarily by tangential or compressive stresses at the bolt-hole edge perpendicular to the direction of the load. This failure is directly related to the width of the specimens (when the width-to-hole diameter ratio (w/d_h) is small) and it is brittle [52].
b) Shear-out failure: results primarily from shear failures of the fibre and matrix. It is principally related to the edge distance from the centre of the bolt to the edge. Shear-out failure is also regarded as a consequence of bearing failure with short edge distance [49]. Regardless of the edge distance, shear-out failure is prevalent in highly orthotropic laminates (rich in 0-degree and deficient in 90-degree plies). Like net-tension failure, shear-out failure is catastrophic.
c) Bearing failure: is caused primarily by the compressive stresses acting on the hole surface. This failure is mainly associated with the delamination of the plies and buckling of the fibres. It is a gradual, progressive and non-catastrophic failure, making it a desirable failure mode [53] (refer to Section 4.1.2). Due to its importance, interest focuses on bearing failure in this thesis. It is well known that full bearing strength is only attained when the width (w) and edge distance (e) are above certain minimum values. However, for some multi-fastener configurations, tensile failure cannot be avoided. Bearing failure may be initiated at lower load levels than the brittle net-section mode [54]. The peak strength of a bolted joint is said to occur at a geometry associated with net-tension failure or bearing failure, followed by an abrupt change to net-tension failure [55]. It should be noted that different definitions of bearing strength have been used in the literature. In the ASTM standards (ASTM D953 or ASTM D5961), the bearing strength is based on 4% or 2% permanent bolt-hole deformation. Some authors calculate bearing strength corresponding to the first onset of non-linearity in the load-displacement curves and some consider the first load drop or the ultimate maximum load. A detailed discussion of these definitions is provided by several authors [51, 56, 57].

d) Pull-out (tear-out) failure: is a secondary failure and only occurs after bearing failure. This failure mode is not that common.
e) Cleavage failure: is a secondary failure mode and it occurs after bearing failure, or it is triggered by incomplete net-tension failure. The cleavage failure load is lower than that of a joint that fails in bearing or net tension. Cleavage failure generally occurs in FRP laminates in which the percentage of 0-degree fibres is high and 90-degree plies are insufficient [49, 58]. It is also very common in specimens that are relatively wide but have a short edge distance. This failure mode might be catastrophic in nature [59].
f) Fastener pull-through failure: the main failure mechanism for fastener pull-through is the delamination of the plies at the edge of the fastener head [60-63]. This failure mode is mostly associated with countersunk bolts. Out-of-plane loading can cause partial or complete pull-out of the bolt from the composite structure. Increasing the diameter of the bolt increases the bolt pull-through failure load [60]. The failure mode in single-shear joints might be bolt pull-through failure instead of bearing failure, even though it can be designed for bearing failure, due to the secondary bending moment caused by the eccentricity of the load. This is more dominant for thin laminates [64].
g) Bolt failure: is caused by the combination of bending and shear stresses in the bolt. This type of failure is the least common failure mode for composite joints. However, bolt bending is much more significant for composites compared with metals because, for a given load, composite members are thicker and more sensitive to non-uniform bearing stresses [65]. It is the bolt bending or tilting which gives rise to the non-uniform through-thickness stresses in the laminates. To some extent, bolt bending occurs in every joint loaded in shear. In order to avoid bolt bending, the hole-diameter-to-thickness ratio (d_h/t) should be kept greater than 1.0.

In summary, the most common failure modes are net-tension, shear-out, bearing or cleavage failure. The design of bolted joints usually aims to prevent failure by either bolt pull-through or bolt failure.

4.1.2 Bearing failure mechanism at microscopic level

The failure modes presented above are categorised as the macroscopic failure modes in bolted joints. At microscopic level, the failure modes in the vicinity of the hole include the tensile, compressive or shear failure of fibres, matrix cracking and delamination between the plies.

Owing to the importance of the bearing failure mode, detailed experiments, including acoustic emission, X-ray and microscopic examinations, in order to understand and characterise bearing failure and damage development in bolted joints, can be found in the literature [53, 66-71]. Determining the location, failure mode and load level of damage initiation is essential in order to capture the entire bearing failure process.

Bearing failure is characterised as consecutive, accumulated damage to the plies in the laminate, which render the failure of the joint as ductile at macroscopic level. In spite of this, before the failures that can be detected in the load-displacement curves, the bearing damage in the material starts at load levels where the load-displacement curves are still linear. As it is very difficult to determine the load level for each damage initiation and type in the literature due to material dependence, research agrees that the failure starts with resin cracks and fibre micro-buckling at load levels that are less than 50% of the first load drop in the load-displacement curves, as depicted in Figure 4.4. According to Ireman *et al.* [67], resin cracks can already start at a load level of 25% of the first load drop. The fibre micro-buckling firstly occurs in the 0^{o} plies in the laminates in the form of kink bands. The fibre micro-buckling in the contact region between the bolt and the hole accumulates and triggers delamination between the surrounding plies and the formation of shear cracks in the through-thickness of the laminates. These failures start to become visible in the load-displacement curves in the form of irregularities or non-linearities at load levels higher than 70% of the first load drop, as shown in Figure 4.4. The accumulation and propagation of through-thickness delamination and the shear cracks are the cause of the fracture and the load drops in the load-displacement curves. As stated by Xiao and Ishikawa [68], the multiple load reduction points appearing in the load-displacement curves after the first load drop can be attributed to through-thickness shear cracks occurring and progressing intermittently.

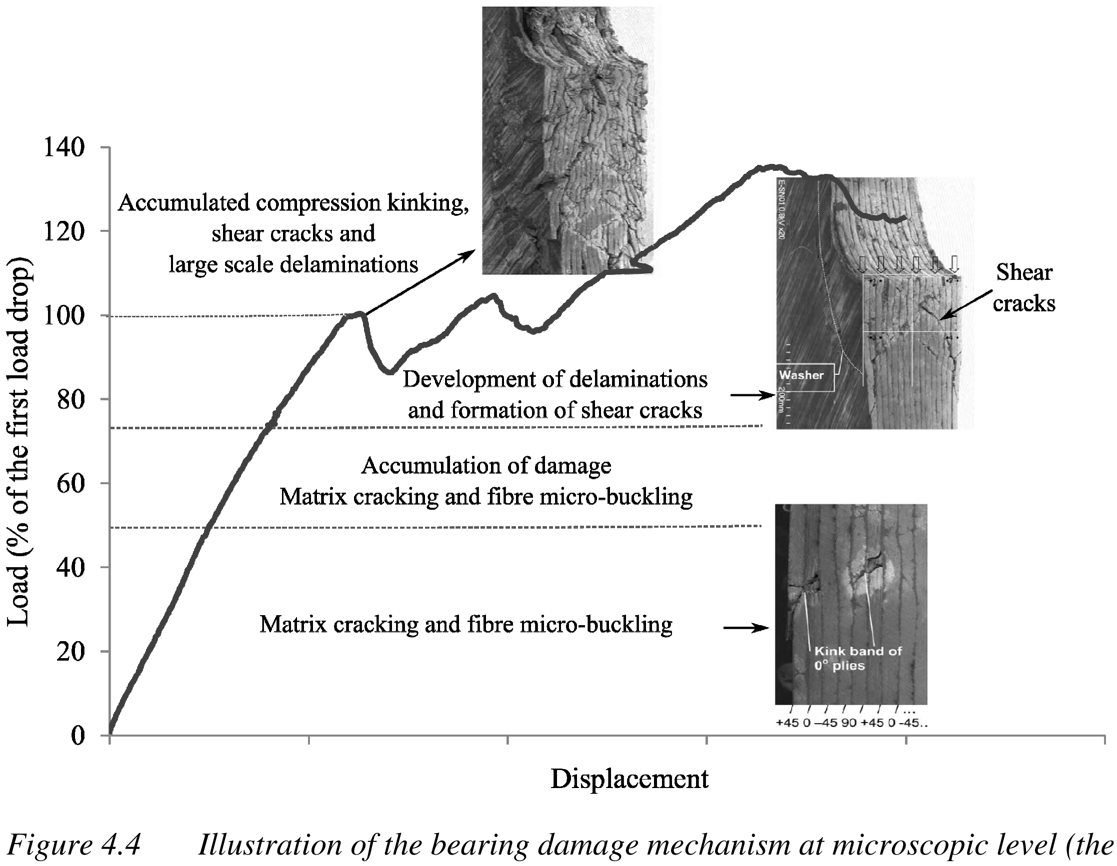


Figure 4.4 Illustration of the bearing damage mechanism at microscopic level (the pictures are used to help illustrate the damage from [68])

In the case of joints with lateral constraint provided by pretensioned bolts, the bearing failure develops in a similar manner to that described above, but failure occurs at higher loads. The lateral constraint prevents delamination under the washers and, as a result, compressive damage expands in the in-plane direction in the unconstrained area and progresses in the form of large delaminations and through-thickness shear cracks outside the washer region.

It is worth mentioning that this mechanism occurs primarily in quasi-isotropic lay-up laminates. For pultruded laminates, in which the 0-degree plies in the mid-section of the laminate dominate, the mechanism might be slightly different. For instance, a stiffness reduction before a sudden load drop is not common in pultruded laminates tested in loads parallel to the 0-degree plies [57]. To the author's knowledge, detailed investigations to determine the micromechanics of bearing failure for pultruded sections have not been performed.

4.1.3 Parameters affecting joint performance

The mechanical response of composite bolted joints can be complex due to the inherent complexity of composite materials and the various parameters that influence joint behaviour. These parameters can be basically divided into three groups: i) material parameters, ii) fastener parameters and iii) design parameters.

i. Material parameters

- *Fibre type and orientation*: the fibre types, orientations and proportions in the different lamina of the composite material influence the stiffness, strength and failure mode of the joint. Wang *et al.* [72] detected numerically that the failure mode of a joint with a stacking sequence $[0^o]_{40}$ was shear out and the failure mode of a joint with a stacking sequence $[45^o/0^o/-45^o/90^o]_{5s}$ was net tension. It was also demonstrated experimentally by Abd-El-Naby and Hollaway [73] that laminates composed of fibres mainly oriented in 0^o were unable to achieve bearing failure, but they failed in a shear-out mode because of the low shear strength of the material. Based on the studies in the literature, the maximum static strength of composite bolted joints is frequently realised by quasi-isotropic patterns $[0/\pm45/90]_S$ [65, 66, 74]. The presence of the 0° layers is important to maximise the stiffness and the ultimate failure load of the joint. The bearing strength of joints is increased when the fibre proportion at 0 degrees is increased in the formation of the laminate [71, 75-77]. McCarthy *et al.* [56] observed experimentally that joints with zero-dominated lay-ups are stiffer than those with quasi-isotropic lay-ups. Layers with 90° are important to resist the displacement of the bolt and avoid shear-out failure. Accordingly, the sudden failure of the component is delayed and the structural reliability increases [71]. Introducing ± 45° layers is important to avoid shear failures and to maximise the bearing load. Collings and Beauchamp [78] demonstrated the importance of ± 45° layers in increasing the bearing stiffness of joints. In pultruded sections, the presence of rovings (unidirectional fibre bundles) plays a huge role in achieving bearing failure when the sections are loaded parallel to the pultrusion direction. When the pultruded laminates are loaded at off-axes angles (starting from 30^o), Turvey [79] observed that the bearing failure is almost non-existent and the rovings influence the propagation of the cracks during failure. Regarding the different types of fibre, such as glass and carbon, Kretsis and Matthews [80] found that the effects of width, edge distance, hole size, bolt pre-tension load and the stacking sequence were generally similar for both GFRP and CFRP laminates. However, all-carbon materials display more brittle failure than all-glass and hybrid materials [81].

- *Stacking sequence:* it should be noted that the stacking sequence in this thesis connotes the fashion of stacking the oriented fibres (plies) with the same proportions in the composition of laminates with the same thicknesses – for instance, stacking the same proportion of 0- and 90-degree oriented fibres in two different ways, such as $[0_6/90_6]_S$ and $[90_6/0_6]_S$. Experimental tests indicate that the stacking sequence usually has a negligible effect on the ultimate bearing failure loads of joints [75, 82]. However, the micromechanics of failure and delamination bearing strengths are completely influenced by the stacking sequence of composite laminated plates [80, 82]. Research shows that 0-degree layers should not be placed on the laminate surfaces because they tend to fail by splitting, buckling and breaking away from the laminate under bearing loads [66, 83-85]. Instead, 90^o layers are preferred as they prevent the 0^o layers buckling or delaminating [86]. Collings [58] observed that the stacking sequence can affect the specimens that fail in bearing more than the ones failing in the shear-out or net-tension failure modes. Since the material and fibre orientation used in the stacking sequence for composing the laminate affect the strength of the bolted joints, different combinations of composite materials, such as substituting some CFRP plies with titanium plies in the aviation industry, have also been tried to increase joint strength. The studies show that the strength and efficiency of CFRP joints can be dramatically increased [87-89].

ii. Fastener parameters

- *Fastener type:* the type of fastener can influence the performance of the joint. Studies [67, 90, 91] have revealed differences in joint strength, stiffness and failure mode between protruding head bolts and countersunk ones. Countersunk fasteners usually yield a lower bearing strength compared with protruding head fasteners [56, 67]. This effect is less pronounced for thicker laminates [67]. Fastener heads should be designed with as much bearing surface area as is practicable, because the larger area improves the pull-through and delamination resistance in composites. Metallic bolts are preferable to FRP fasteners, because FRP fasteners might be weaker than the joined members, resulting in failure in the FRP fastener before any failure takes place in the joined members [92]. Matharu and Mottram [93] tested the effect of bolt threads bearing into the laminate. The preliminary results showed that the stiffness of the threaded bearing joints is lower than that of the plain shank bearing joints, but the bearing strength is similar.

- *Pretensioned bolt:* lateral constraint (clamping pressure) provided by the bolt tension can increase the joint bearing strength, as is demonstrated in many studies [66, 67, 73, 80, 82, 94-100]. The increase in strength is dependent on the clamping area, as shown by Abd-El-Naby and Hollaway [73]. The improvement in strength capacity is mainly due to the suppression and delay of delamination in the clamping area and partially due to the load being transferred by friction forces. The ultimate strength of the joint increases as the clamping pressure, provided by the bolt tension, increases up to a saturated value [58, 82]. The maximum clamping pressure that can be transferred to the laminate is limited to the through-thickness compressive strength of the laminates to avoid any damage. The failure load for clamped joints is also dependent on the thickness of the laminates. Thin laminates fail at higher loads if clamped [49]. Cooper and Turvey [97] observed that fully torqued joints require larger edge-to-hole-diameter (e/d_h) and width-to-hole-diameter (w/d_h)

ratios for bearing failure to develop. It might therefore be the case that the failure changes from bearing mode to another mode if the joints are fully clamped. The clamping condition also affects the displacement characteristics of the joint. Joints with a fully pretensioned bolt show less movement than joints in which the bolt is finger tight or free [92]. However, the stiffness of the joint is not increased by increasing the bolt tension as found by Cooper and Turvey [97]. One concern when it comes to the pretensioned bolt in composite joints is the relaxation and reduction of the bolt pre-tension load over time due to the resin creep deformation of the composite laminates. This relaxation is even more pronounced in high temperature and moisture conditions [101-103]. The loss of bolt tension does not translate to the same loss of joint strength [101, 103].

- *Clearance:* has been found to have major effects on joint stiffness (increased clearance results in reduced joint stiffness) [56], the failure initiation load (a significant reduction in the load at which initial failure occurs) [104], the fatigue life (joints with one loose-fit hole have a shorter fatigue life than joints with all neat-fit holes [105]) and the load distribution in multi-bolt joints [105, 106]. The decrease in joint stiffness and damage initiation load is a direct consequence of the reduction of the contact area between the bolt and the hole. Looking at the tests performed in the scientific literature, it is noteworthy that the ultimate bearing strength depends on the extent of the tested clearances. A fair number of the tests include clearances in the range of aircraft applications, up to 3% of the hole diameter. These tests show that improvements in failure load and bearing strength are seen after reducing the clearance [107, 108]. Pierron *et al.* [109] tested specimens with up to 11% clearance and losses of up to 30% in joint ultimate strength were recorded. Yuan *et al.* [110] reported significant ultimate bearing strength reduction in joints with clearances of more than 1.6 mm. Tests performed by Zafari and Mottram [111] also show that the bearing strength decreases with increasing clearance. However, in their tests, the bolt diameter was variable as well; this is a parameter that affects the bearing strength results and it is therefore difficult to relate the result to the clearances alone.

- *Interference fit:* the bolt-hole fit conditions have different definitions. Interference-fit joints are when the bolt diameter is slightly larger than the hole diameter and the bolt is pushed into the hole. The interference (I) can be presented as a percentage calculated using Equation (4.1), in which d represents the diameter:

$$I(\%) = \frac{d_{bolt} - d_{hole}}{d_{hole}} \times 100 \tag{4.1}$$

  If the diameter between the bolt and hole is the same, the joints are defined as neat-fit joints. The benefits of interference-fit joints compared with neat-fit joints are: i) reduction in fastener rotation, which is more severe for thick laminates, ii) lower joint deflection [112], iii) improved fastener load sharing, iv) reduction in relative fastener flexibility, v) reduction in hole elongation, especially during fatigue, thereby improved fatigue performance [112-114], and vi) increased ultimate bearing strengths [95, 107, 113, 115]. The ultimate bearing strength is only increased if the interference fit is correct and not excessive. Wei *et al.* [113] tested specimens with different interference-fit values and found that an interference fit of 0.5% increased the bearing strength, whereas an interference fit of 3% lowered the ultimate bearing strength compared with a neat-fit joint. Zhao *et al.* [114] indicated that the interference of 0.5%~ 1.5% is more suitable for composites, whereas Kim *et al.* [112] commented that the interference fit should be kept under 1% in order not to degrade the performance of the joints. Excessive interference fit causes delamination around the hole in the joint [116]. It is the low interlaminar strength of composite materials that restricts the use of interference-fit joints [116]. Kim *et al.* [112] found that the samples with 1% interference fit have an approximately six times longer average fatigue life than the neat-fit samples. Kim *et al.* [117] and Pradan and Babu [115] argue that fatigue enhancement using the interference-fit technique may be due to local pre-compression stresses induced by the interference fit, thus reducing the magnitude of the resultant tensile stress after actual mechanical loading. Kim *et al.* [112] demonstrated that the fabrication process can also affect the performance of the connections with interference fit. The vacuum-infused samples showed visible fatigue life improvement due to interference fit, while the hand lay-up and hybrid (vacuum infusion + hand lay-up) methods showed moderate improvements.

- *Friction:* plays a major role in bolted joints, but there are insufficient studies of the effect of the coefficient of friction between the plates on joint behaviour. Schön [118, 119] studied experimentally the coefficients of friction between several materials used as plates in composite bolted joints. He observed wide variability in the coefficient of friction depending on the materials in contact, surface ply orientations and the wear of the surfaces caused by cyclic movements. The coefficient of friction for pultruded FRP on FRP has been found by Mottram to vary between 0.14-0.22 [120]. Friction plays a major role when bolt tension is applied to the joint, because the bolt tension can add to the load transfer through friction [49]. However, for low values of friction coefficients, an increase in the bolt tension influences slightly the joint stiffness and strength [121]. Today, any load transfer by friction is ignored in the design of bolted joints.

iii. Design parameters

- *Joint geometry:* it is well known that the failure mode and strength of bolted joints are strictly influenced by the geometric parameters. For instance, when the edge distance-to-hole diameter ratio (e/d_h) and width-to-diameter ratio (w/d) are increased, the bearing strength reaches higher values up to a threshold ratio value and it then remains reasonably constant [96, 122]. The ultimate bearing strength is higher for smaller diameters [58, 66, 123]. Collings [58] noted that this holds true when no lateral constraint is imposed on the laminate. When lateral constraint is present, the differences in bearing strength for various hole sizes disappear. Mottram and Zafari [57] also found that the bearing strength decreases as the bolt diameter-to-laminate thickness (d/t) ratio increases for pultruded elements. It is worth to mention that the clearance also increased together with d/t ratios in their tests, which could be another factor in terms of strength reduction. The increase in bearing strength with smaller diameters can be associated with the hole-size effect. The hole-size effect suggests that, for tension specimens containing various-sized holes, the larger holes cause greater strength reductions than the smaller holes [124]. On the other hand, Ascione *et al.* [125] observed that the bearing failure strength increases linearly with an increase in bolt diameter for unidirectional (UD) laminates. For biaxial laminates, this increase was non-linear. In the light of these conflicting results, the relationship of the bearing strength to the bolt diameter remains unclear. The laminate lay-up orientation is perhaps one of the causes of these conflicting results. In pultruded FRP bolted joints, Turvey [79] reported that the initial stiffness increases as the width-to-bolt diameter ratio (*w*/*d*) increases. The laminate thickness has a significant effect on the joint stiffness and ultimate load, both of which rise with increases in joint thickness [126]. When it comes to laminate taper, weight savings may be achieved by reducing the thickness of the laminates outside the overlap region of the joint. Studies show that tapered joints display only moderate differences in joint stiffness, bearing strength and load distribution when compared with similar constant thickness specimens [64, 126]. It was also demonstrated that the taper type had a significant effect on secondary bending and thus on the final mode of failure in the joint [126]. Cooper and Turvey [97] observed that the geometric parameters can also be dependent on bolt torque; for example, by increasing the bolt torque, the critical *e*/*d* and *w*/*d* ratios to achieve bearing failure increase significantly. The efficiency of a bolted joint with respect to its geometry is highlighted in Figure 4.5. Joint efficiency is defined as the ratio of the joint strength to the strength of the weakest joined part [127]. This figure reveals that the maximum attainable bolted joint efficiency is 40% compared with the strength of the base material.

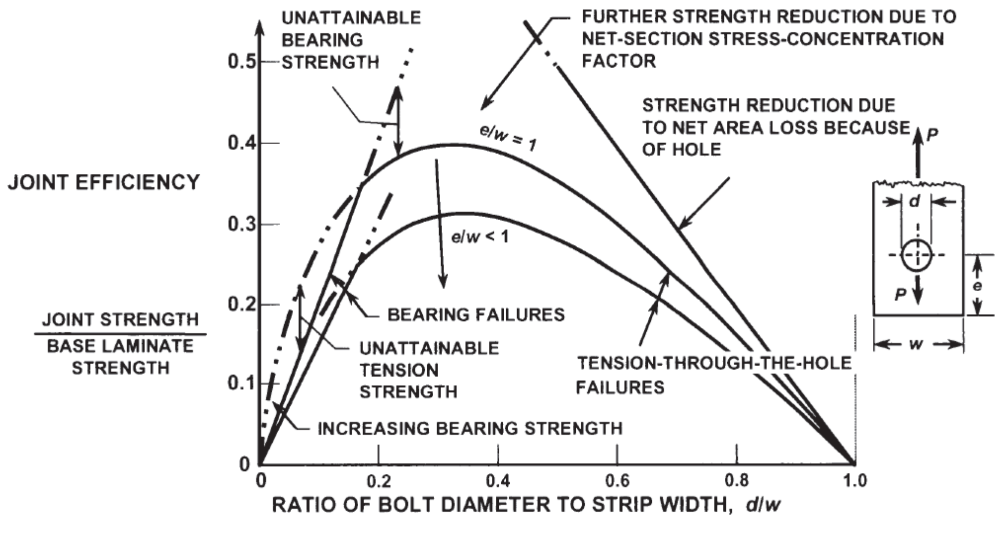


Figure 4.5 Bolted joint efficiencies for composite laminates as functions of joint geometry [74]

- <u>*Type of joint:*</u> differences are detected in joint behaviour based on the joint type. For example, single-lap joints result in significant stress concentrations in the thickness direction and lower bearing strength than the double-shear bolted joints. Secondary bending influences the various microscopic and macroscopic failure modes and thus has the potential to change the mode of failure and affect the ultimate failure load [96]. It also lowers the joint stiffness, which is more significant under compressive loading than tensile loading [128]. Double-lap joints are better for cyclic loading and are generally stronger. Moreover, the number of bolts, bolt rows and bolts per row are among other factors influencing the performance of bolted joints.

The dependence of joint behaviour on so many parameters makes the design of bolted joints fairly complex. The maximum joint efficiency in composites tends to be less than that of metals. In addition, it is stated that the joint efficiency of bolted joints is lower than that of the bonded ones. However, in some situations, bolted joints can be more efficient than bonded joints. Turvey and Gode [96] observed that single-lap, single-bolt joints in pultruded sections can have a load capacity that is up to 20% higher than that of equivalent single-lap bonded joints.

4.1.4 Bolted joints with inserts

The efficiency of bolted joints in composites is less than in metallic structures, as mentioned in the previous section. Due to this low efficiency, new techniques need to be developed to improve joint efficiency. One method proposed by several researchers is to use inserts placed between the bolt and the laminate. The inserts can be bonded or interference fitted. Initially, the bonded inserts were used to protect composite laminates from damage caused by the repeated installation of the bolts. The inserts provide a localised plastic zone, which reduces the stress concentration on the composite material, thereby providing stress relief [55]. Greater strength in the joints that fail in bearing is therefore expected.

The types of insert used in the studies found in the literature are shown in Figure 4.6, where d represents the bolt diameter, d_h the hole diameter and t the laminate thickness. Reference to these types of insert is made in the following.

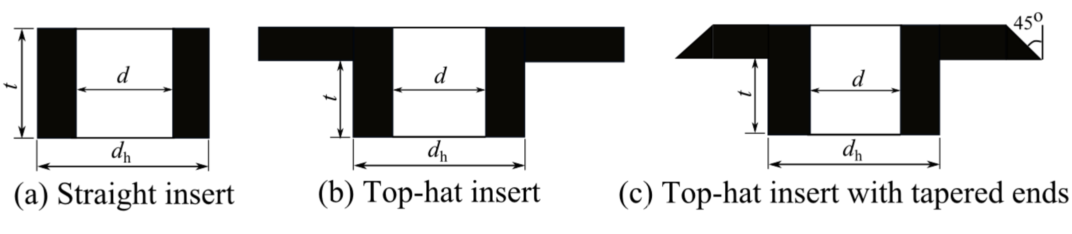


Figure 4.6 Types of insert found in the literature

Hoa *et al.* [129] tested the use of stainless steel straight inserts to facilitate the fastening of single-lap bolted joints. The joint efficiency of the specimens with inserts was found to be slightly higher than that of the bolted joints alone.

Nilsson [130] compared the strength of double-shear, quasi-isotropic CFRP composite bolted joints with bonded 2 mm thick metallic straight inserts made of steel and aluminium. He found a strength increase of 55% for the aluminium insert and of 30% for the steel insert when compared with an all-composite joint. The bolted joint with a steel insert also produced a 13% stiffer joint. The lower strength of the joints with steel inserts was due to the primary tension failures in the adhesive, caused by the steel inserts, owing to the higher stiffness of the insert compared with the aluminium inserts. The failure mode of joints with inserts was altered from bearing to tension mode combined with adhesive failure, probably due to an increase in hole diameter while keeping the width constant. When the metallic inserts were not bonded, the strength was reduced by 20% and 10% for the aluminium and steel inserts compared with those with bonded inserts.

Herrera-Franco and Cloud [131] studied experimentally GFRP composite, double-shear bolted joints with and without 1.6 mm thick bonded circular straight inserts made of plastic or aluminium and focused mainly on the stress and strain distributions in the bearing region. They observed substantial reductions of the stresses and strains in the bearing region when aluminium inserts were used, but not significant reductions for the plastic inserts. The insert helped to distribute the stresses and strains more evenly around the hole area. These reductions were more effective before the glue around the insert failed. However, even after the failure of the glue, the stresses and strains around the hole were still lower than those of the specimen without any insert. The final strengths were not compared.

Rufin [132] utilised cold expansion as a means of installing metal straight inserts in fastener holes. A comprehensive test programme involving mechanically fastened joints in composites with adhesively bonded and cold-expanded grommets showed that, in general, cold-expanded grommets perform comparably to, or better than, bonded grommets.

Mirabella *et al.* [133] obtained an increase of 100% in the bearing strength of single-lap, bolted composite joints by bonding a top-hat aluminium insert, shown in Figure 4.6(b), when compared with connections without inserts. The benefit in terms of bearing strength with straight inserts was minor.

Camanho and Matthews [134] investigated numerically the use of bonded circular straight metallic inserts made of steel and aluminium for double-shear CFRP composite bolted joints. They observed that the stresses around the hole region were reduced for both insert types, 15-20% less for the steel inserts compared with the aluminium inserts. However, the stresses in the adhesive bond for the steel inserts were increased due to the higher stiffness of the steel insert, leading to the premature tension failure of the adhesive. This study was in agreement with the results presented by Nilsson [130]. Due to the adhesive failure before the exploitation of the full strength of the composite laminate, the strength improvements in the joints with the inserts were very small. A parametric study of the effect of the thickness of the metallic insert (thickness 10-14.3% of the hole diameter) was also performed. The increase in insert thickness led to reduced stress concentrations, but this was accompanied by higher tensile stresses in the adhesive. The authors concluded that inserts with low stiffness are preferable, in the case of bonded inserts, in order to delay the failure of the adhesive bond.

Rispler *et al.* [55] utilised the evolutionary structural optimisation method to optimise the size and shape of the insert to be used in bolted joints in order to reduce the peak stress concentrations and consequently increase the joint efficiency when the failure mode is bearing. Experimental tests were performed with the optimised inserts and regular circular inserts, see Figure 4.7. No change in stiffness was recorded for the specimens with inserts compared with the ones without inserts. However, a substantial reduction in shear strain concentration in the pin-loaded holes was recorded for the specimens with inserts. The optimised inserts yielded a further reduction of 55% in the maximum shear strain compared with the circular inserts. However, these optimised inserts yield the best results when the direction of the load is known. The authors concluded that, when the direction of the principal load is not known, the optimum solution is to bond circular inserts.

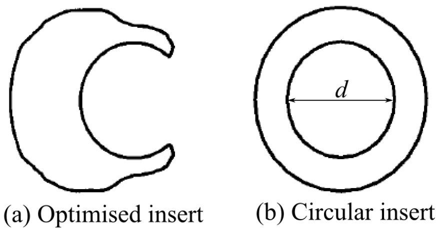


Figure 4.7 Top view of the optimised and circular insert types used by Rispler et al. *[55]*

Camanho *et al.* [135] studied numerically and experimentally the use of bonded aluminium inserts for single-shear lap joints. They focused on the design of the insert geometry in order to increase the load at which the adhesive bond failure takes place and found that the most appropriate insert geometry was the insert with tapered outer ends, as shown in Figure 4.6(c). An increase in the strength of single-shear lap joints with bonded inserts with tapered ends was obtained compared with joints without inserts. The authors stated that the increase in joint strength was due to a higher load before adhesive failure and the additional load being transferred by shear stresses occurring at the laminate-adhesive interface in the hat regions. However, the authors did not mention the fact that a major contribution to the increase in load is the confinement of the through-thickness expansion of the laminates, thus delaying the failure in the laminate.

Kradinov *et al.* [136] proposed a method based on a complex potential theory in conjunction with a variational formulation, to determine the bolt load distribution in single- and double-lap joints with metallic straight inserts. The study demonstrated that the change in the thickness of the laminates and the presence of inserts did not alter the bolt load distribution, but they significantly influenced the behaviour of the contact stresses, which are critical for failure predictions.

The latest research on bolted joints with straight inserts has been performed by Mazraehshahi and Zakeri [137]. They performed parametric analyses using the finite element method. The results revealed that steel inserts exhibit better behaviour regarding stress concentrations in the hole in comparison with titanium or aluminium inserts before any adhesive failure. An increase in insert thickness and adhesive stiffness reduces the stress concentrations in the vicinity of the holes. These results are in agreement with the findings of Camanho and Matthews [134]. Mazraehshahi and Zakeri [137] also found that the tangential and radial stress concentrations are considerably increased, if clearance exists between the insert and the hole.

The outcome of this research demonstrates that the metallic inserts help to reduce the stress concentrations around the hole of the composite when bonded or interference fitted. In the case of bonded inserts, the stress concentration relief is more pronounced before any adhesive bond failure, because it is the adhesive layer which modifies the transfer of forces and engages the entire hole in bearing the loads. When the bonded layer fails, the inserts are more efficient for single-lap joints than double-lap joints. This is associated with the secondary bending effect of the single-lap joints. The joints with inserts resist the bending more effectively, providing a more rigid joint, and, as a result, a relatively stronger joint. Another outcome of the research is that the inserts with hats are more efficient than the straight circular inserts in terms of joint strength.

All the research on this topic is conducted for "finger-tightened" bolts and the effect of the bolt tension is not studied. In addition, the studies lack the presence of clearance between the bolt and the inserts. These two parameters were of interest to investigate in this thesis and they are presented in Chapter 5.

4.1.5 Design methods

Today, the design of composite bolted joints in civil engineering applications is based on the EuroComp design methods. The EuroComp design methods are based on the aerospace engineering and there are some limitations to these design methods, which have been criticised by several authors [138-140]. One semi-empirical method for the design of bolted joints, which has been developed specifically for pultruded sections, is based on a slight modification of the Hart-Smith method by Rosner and Rizkalla [141]. However, coefficients utilised in the developed formulas need to be determined experimentally for each material thickness. Even though these methods might be useful, they are fairly limited and development of the design methods is required. Initiatives have been taken to develop design codes for composite bolted joints in the USA and Europe. Interest has focused primarily on joints in pultruded GFRP sections. In 2010, a pre-standard for the load and resistance factor design (LRFD) of pultruded fibre reinforced polymer (FRP) structures was developed by American Society of Civil Engineers (ASCE). It contains a chapter on the design of bolted joints [142]. This pre-standard is expected to develop into an official ASCE standard, which will allow structural engineers to use pultruded FRP products with confidence. It should also be mentioned that the major pultrusion companies have developed their own so-called design manuals for composite bolted joints (see for example http://www.creativepultrusions.com/, http://www.fiberline.com/, http://www.strongwell.com/). A more detailed discussion of the design methods for composite bolted joints is given by Turvey [143] and Coelho and Mottram [144].

4.2 Adhesively bonded joints

Various concepts are used for bonded joints. They include single laps, step laps, scarf laps, and so on, as shown in Figure 4.8. One main principle when designing bonded joints is to ensure that the joint works primarily in shear and compression and to minimise direct tensile, cleavage or out-of-plane peeling forces, because most adhesives display higher shear and compressive strength than tensile and peeling strength.

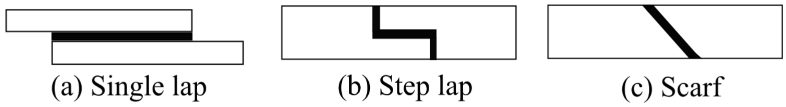


Figure 4.8 Examples of adhesively bonded joint constructions

The structural adhesives can be brittle or ductile, as shown in Figure 4.9. The stress-strain curves of the adhesives are generally non-linear in either tension or shear. Even the brittle adhesives show a slight non-linearity before final fracture.

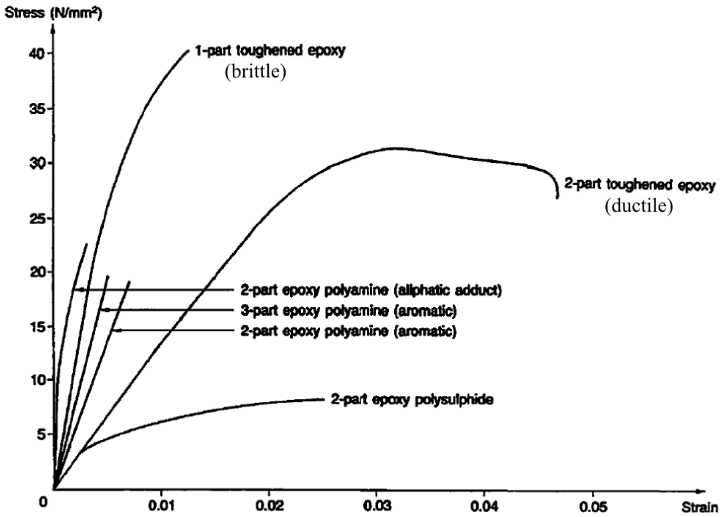


Figure 4.9 Tensile stress-strain behaviour for a range of epoxy adhesives (adapted from [145])

Even though it is often claimed that adhesive joints provide a more uniform stress distribution within the joint compared with bolted connections, stress concentrations are still present. In single-lap joints, shear and peeling stresses generating from bending effects due to load eccentricity are present. These stresses are concentrated at the ends of the bonded joints, as shown in Figure 4.10.

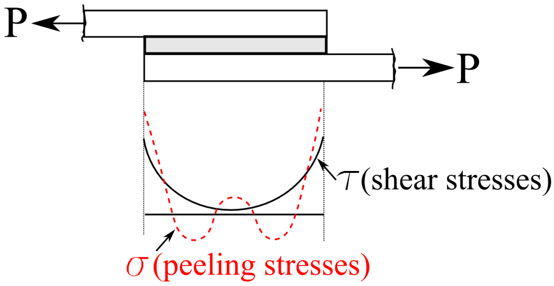


Figure 4.10 Shear and peeling stress distribution in the adhesive layer in a single-lap bonded joint

The shear-stress distribution in these joints is sensitive to the adhesive quality, adherend rigidity and overlap length. If the adherends are assumed to be rigid and the adhesive deforms elastically, the shear-stress distribution in the adhesive is linear, as shown in Figure 4.11(a). In reality, the adherends deform elastically in tension causing shear stress concentration at the end of the joints, see Figure 4.11(b). The first approximation is also valid for short overlap joints, while a more refined analysis of shear-stress concentrations should be performed for long joints.

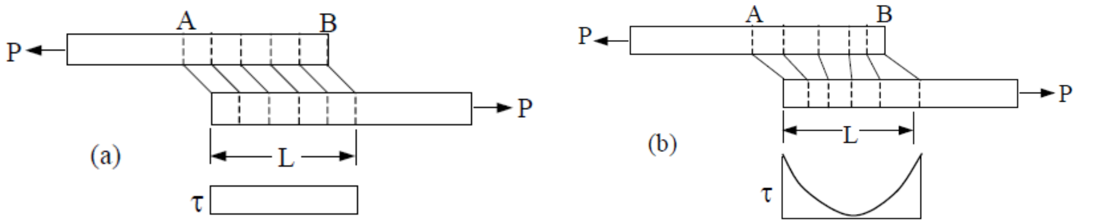


Figure 4.11 Shear-stress distribution in single-lap joints: a) with rigid adherends, b) with elastic adherends (adapted from [101])

The adverse peeling stresses can be avoided by eliminating eccentricities within the joint and employing a double-lap, scarf, or similar configuration. However, even in double-lap joints, bending effects exist to some extent, causing peeling stresses at the joint, as illustrated in Figure 4.12.

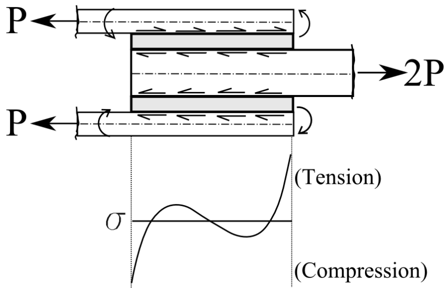


Figure 4.12 Peeling stresses in the adhesive in a double-lap joint (adapted from [101])

In order to reduce the stress concentrations at the ends of the joints, either providing suitable tapered laps or adding adhesive fillets are effective options [146, 147].

4.2.1 Failure modes

Bonded joints can basically fail in three modes, as shown in Figure 4.13, which can be summarised as follows:

i. *Adherend failure:* failure of the adherend material occurs in tension or in the form of delamination/fibre-tear failure within the FRP laminas, starting at locations of stress concentrations at the end of the overlap. The ideal failure mode is tensile failure of the adherend, because the entire capacity of the adherend is utilised, but this happens very rarely in reality.

ii. *Adhesive failure:* failure of the adhesive, also known as cohesive failure, occurs due to excessive shear or peeling strains at the stress concentration points at the ends of the overlap. Depending on the type of the adhesive, this failure might be caused by brittle facture.

iii. *Interface failure:* failure at the interface between the adhesive and the adherend is also referred to as adhesive failure in some literature. This failure occurs due to insufficient adhesion. It leads to a failure load below the elastic limits of both the adhesive and the adherends and it should therefore be avoided. This type of failure is not considered in the design of bonded joints. The design of bonded joints is done by considering cohesive failure or failure in the adherends.

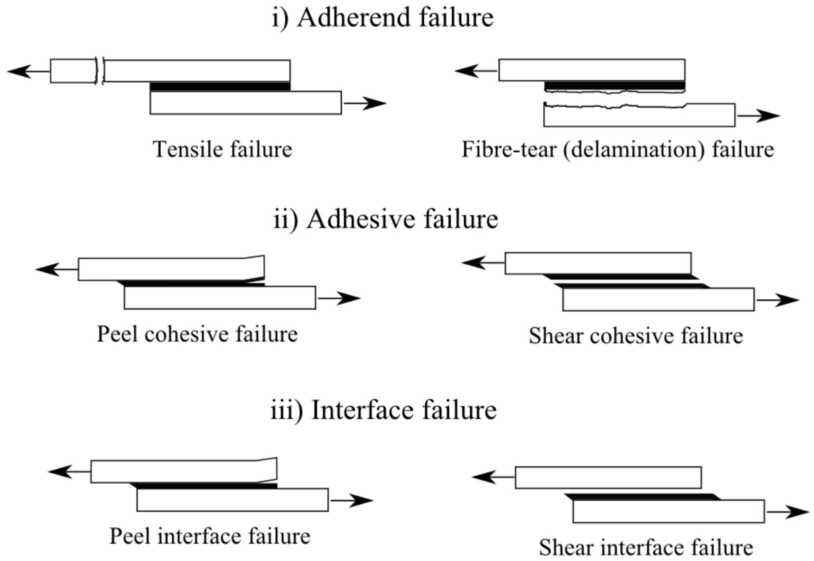


Figure 4.13 Basic failure modes of adhesively bonded joints

4.2.2 Parameters affecting bonded joint performance

The performance of bonded joints is affected by several parameters, which are as follows.

i. <u>Material parameters</u>

The material parameters of the composite and the adhesive affect the performance of bonded joints.

In pultruded structures, the number of interfaces between the mat layers and unidirectional (UD) roving layers affect the strength of bonded joints. Keller and Vallée [148] demonstrated experimentally that the combined through-thickness tensile and shear strength of laminates with a larger number of interfaces is lower than that of those with one interface. It should be noted that this is valid, if the failure mode is fibre-tear failure in the outer mats of adherends.

The properties of the structural adhesives, including mechanical, physical and chemical ones, are important parameters for selecting adhesive types for the design. In bridge applications, brittle adhesives are generally used, due to their advantages of high stiffness and creep resistance.

The stiffness of the FRP material in relation to the adhesive stiffness also affects the strength of the joint. As a general rule, adhesives that are less rigid than their adherends are selected, so that stress concentrations within the joint can be minimised [65]. Stiffer adherends promote a more uniformly loaded joint, while flexible adherends have little bond load transfer at the centre of the overlap (see Figure 4.11(b)). In addition, unequal adherend stiffness at both ends of the joint adversely affects the joint strength. So, wherever possible, the stiffnesses should be kept approximately equal.

ii. Design parameters

- *Joint geometry:* the geometry of the FRP adherends (thickness, width, length), surface area available for bonding, bond line thickness and overlap length are all important parameters in the design of bonded joints. They influence the stress distribution within a joint.

  In double-lap joints, the thickness of the adherend controls the failure mode and the strength of the joint. For thin adherends, the adhesive shear strength usually exceeds the adherend strength and the weak link will always be in the adherends outside the joint. For thick adherends, the peeling stresses become dominant and the strength limit is set by the peel stresses rather than the adhesive shear stresses [65]. However, this might not be the case if suitable laminate end tapering is used [147, 149].

  As a rule, thinner bond lines are preferred for maximum bond strengths and rigidities, because they are more resistant to cracking when flexed and they display less creep [65]. However, this is not always possible in civil engineering applications, especially if the bonding procedure has to be performed on site.

  In short overlap joints, the shear stress distribution is more uniform than in long overlap joints. In long overlap joints, the adhesive shear stresses are higher at the ends and reduce toward the centre of the overlap. Depending on the overlap length, the stresses in the centre of the overlap can be essentially zero. The strength of the bonded joints converges to a constant value with increasing overlap length [150].

- *Type of joint:* the distribution of stresses in a bonded joint depends on its configuration, thus yielding various strengths. Depending on the requirements and the practicalities, different joint configurations can be selected in the design of a joint. A summary of the most common bonded joints and their usage is given in [65].

iii. Fabrication parameters

- *Surface treatment:* surface preparation is one of the most crucial factors affecting the capacity and integrity of the bonded joint. The production of a roughened surface and cleaning of the contaminants must be ensured prior to any bonding process. Inadequate surface treatment results in failure of the joint before developing its strength.

4.3 Hybrid joints

Hybrid joints, a combination of bolted and bonded joints, are used to benefit from the merits of both types of joint and for increased joint reliability. Adhesive bonding reduces the effects of stress concentrations around the hole and increases joint stiffness, while mechanical fastening provides reliability of the connection strength, robustness and reduces peeling effects. The hybrid joints therefore offer redundant and fail-safe structures. If the adhesive bond were to be damaged, the bolted joint would be beneficial for limiting the damage propagation that may lead to premature and catastrophic failures. Hybrid joints have been regarded as an effective solution for repairing damaged adhesive bonds [151, 152].

Research has shown that hybrid joints have several advantages over joints that use mechanical fasteners or adhesives alone:

- Increased resistance to slipping compared with bolted joints [153]
- Increased stiffness compared with bolted joints alone. Manalo and Mutsuyoshi [153] observed a 65% increase in the stiffness of hybrid joints compared with only-bolted joints
- Higher strength relative to adhesive or only-bolted joints [154-157]
- Higher fatigue life in comparison with adhesively bonded joints due to the presence of bolts [155, 158]
- Less stress concentration compared with only-bolted joints [152]

4.3.1 Mechanical behaviour of hybrid joints

The distribution of load in hybrid joints is related to the relative displacement between the adherends. Based on load-displacement relationships, bolted joints are usually able to tolerate higher displacements than bonded joints. The adhesive bond load path is much stiffer than the load path through bolts and the adhesive bond therefore transfers the majority of the load in the first stage. However, Kelly [159] observed that the bolts are also able to transfer a considerable amount of load depending on the design of the joint. The parameters that affect the load distribution in hybrid joints are defined as laminate thickness, adhesive thickness, overlap length, pitch distance and adhesive modulus. The influence of these parameters according to a numerical study of single-lap joints performed by Kelly [159] are as follows.

- The load transferred by the bolt increases with increasing adherend thickness up to a certain thickness value.
- The load transferred by the bolt increases with increasing adhesive thickness. Kelly tested adhesive thicknesses up to 1.5 mm, but the adhesive thicknesses used in civil engineering applications are usually higher.
- The load transferred by the bolt decreases as the overlap length increases.

- The load transferred by the bolt decreases with increasing pitch distance (bolt pitch distance is defined as the distance between bolts in a row). The pitch distance affects the load capacity of the joint and the mode in which the joint will fail. If the pitch distance is increased, net-tension failure can be avoided.

- The load transferred by the bolt decreases with increasing adhesive modulus. So, if adhesives with a low modulus are used, more load will be transferred via the bolt. This was additionally verified in studies performed by Hoang-Ngoc and Paroissen [160] and Bodjona and Lessard [161]. Bodjona and Lessard [161] demonstrated numerically that substantial load sharing could be achieved, when the adhesive plasticises, if adhesives that carry some level of elastic-plastic behaviour are used.

Depending on these findings, it is possible to design hybrid joints in which the bolt transfers a significant part of the load, thus increasing the strength of the hybrid joints. However, by increasing the strength of the hybrid joints, it is important to ensure that the bearing strength of the material is not exceeded; otherwise, a catastrophic failure might occur, as observed in tests performed by Kelly [158]. Careful comparison of the material bearing strength and adhesive bond strength is therefore necessary to ensure increased joint strength and non-catastrophic failure [10].

The failure of hybrid joints can be characterised in two steps, with the first step involving failure of the adhesive and the second step failure of the bolts, which produces progressive, ductile failure, see Figure 4.14. Vallee *et al.* [162] state that the load-displacement behaviour of hybrid joints should not be regarded as ductile, because the hybrid joints sustain a residual load due to the displacement-controlled test; in a real situation, which is essentially load controlled, the joint would not have been able to exhibit such behaviour. Mottram and Turvey [163] also discuss the fact that the bearing failure and its progressive damage growth in bolted joints do not always guarantee the ductility of a joint. Ductility can only be realised if the joint displacement can be several times greater than at the initial damage load and the higher ultimate load is only reached after this displacement has occurred [163]. Nevertheless, the ability to carry loads after initial failure can contribute to the overall robustness of statically indeterminate structural systems. Unfortunately, the analysis and design of hybrid joints is cumbersome and involves a great deal of non-linear analysis.

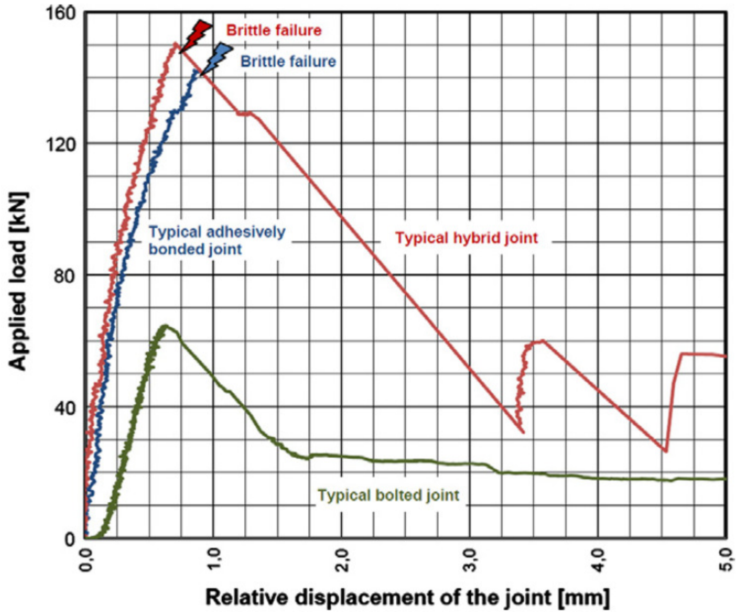


Figure 4.14 Typical load-displacement curves for bolted, bonded and hybrid joints, after [162]

Since the adhesives usually carry most of the load in hybrid joints up to the failure of the adhesive, researchers have tried to come up with different designs for hybrid joints, so that the bolts are also utilised in transferring the load. One such design involves adding attachments with different configurations to the conventional hybrid joints [164-167], as shown in Figure 4.15.

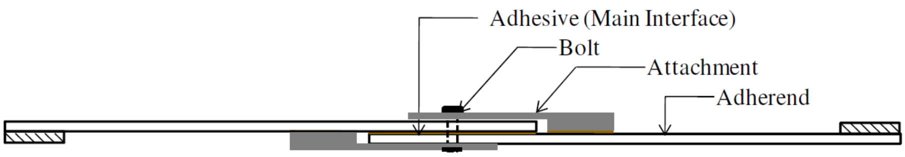


Figure 4.15 Example of a hybrid joint with attachments after [167]

Sun *et al.* [167] compared different designs with composite attachments for hybrid connections. By adding the attachments, the bolts contribute much more to the stiffness and strength of the joint. The load-displacement curves for the different designs studied by Sun *et al*. are shown in Figure 4.16. Other studies on this subject also confirm that the addition of attachments can significantly increase the stiffness and strength of the hybrid connection [164, 165].

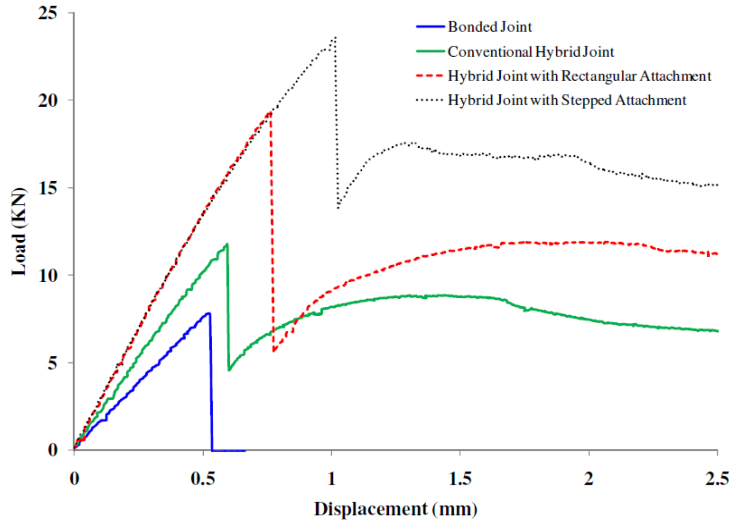


Figure 4.16 Load-displacement curves for hybrid joints with attachments by Sun et al. [167]

The higher strength of hybrid joints with attachments is partially related to the delay in the failure of the adhesive due to the reduction in the peeling and shear stresses in the adhesive joint. This was also observed by Fu and Mallick [155], who compared different washer designs and came to the conclusion that the washers which provide full lateral clamping pressure over the entire overlap area have a better performance than those that provide partial lateral clamping pressure. The clamping pressure covering the lap joint, which is provided by pretensioning the bolts, reduces the peeling stresses at the joint ends. Peeling stresses are the principal reason for the fibre-tear failure of bonded joints. As a result, failure by fibre tear will be either prevented or delayed in the adhesive bond, resulting in a hybrid joint with higher strength. When no clamping is provided, the peeling stresses in the adhesive joint are not necessarily reduced, but the shear stresses are significantly reduced by up to 50%, as demonstrated by Kelly [159] and Hoang-Ngoc and Paroissen [160].

4.4 Interlocking joints

Interlocking joints carry the loads through geometric interference and surface friction between the connected parts. They provide rapid assembly, but the loads that they are able to carry are limited. This is the reason why interlocking joints are fairly frequent combined with bonded or bolted joints. Two examples of interlocking joints that are protected by patents are: a) advanced composite construction system (ACCS) and b) snap-fit connections, which are presented in Paper I. Owing to the load limitations, these joints have not been used for bridges, unless combined with adhesives or bolts. One example in which interlocking joints have been used alone is an electric transmission tower, as shown in Figure 4.17. The entire tower was snapped together like a LEGO® set and was assembled in 20% of the time it takes to assemble a steel tower. In addition, the weight of the composite tower was only half that of a steel tower [7].

Interlocking joints are thought to be fairly suitable for use in the construction of FRP residential buildings (see [168, 169]).

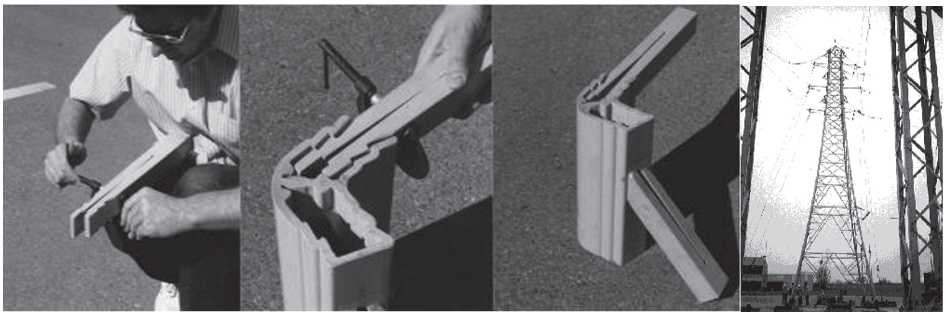


Figure 4.17 Example of interlocking joints used to build an electric transmission tower [7]

4.5 Summary

An overview of the fundamentals of composite joints is given in this chapter. The different types of joint have their own advantages and disadvantages from a structural and applicability point of view and they are summarised in Table 4.1. Interlocking joints are not mature enough to be used in bridge applications and they have therefore been omitted from this summary.

Bolted joints are easy to apply on site, offer the opportunity for disassembly and are easy to inspect visually. Bolted joints represent a common joining method for FRP structures. However, bolted joints exhibit low joint efficiency in terms of strength and stiffness.

Adhesively bonded joints are well suited to FRP materials and they usually provide higher efficiencies compared with bolted joints. Bonded joints provide high stiffness, a high strength-to-weight ratio and high fatigue and corrosion resistance. Despite the advantages of bonded joints, the level of confidence in adhesive bonding for application in bridges is low. In addition, ensuring the application, curing and quality inspection of the adhesive at a construction site is a somewhat difficult task. The disassembly of bonded joints is almost impossible without component damage [170]. Moreover, the cost of on-site bonding is relatively high. Calpham *et al.* [9] state that the bonding work could cost more than 25% of the overall cost of a typical bridge deck replacement schedule based on experience from completed FRP bridge projects. Due to these challenges, Mosallam [65] suggests that it is in the best interests of the civil engineer, at least at the present time, to design the composite joint or connection as only bolted, even if adhesives are used in combination with mechanical fasteners.

Hybrid joints are used to combine the merits of both joining techniques, bolted and bonded, to obtain fail-safe, redundant joints. Hybrid joints have advantages when it comes to on-site assembly of bridge elements, as the parts are fixed by bolts during the bonding process and adhesive cure. In addition, the performance of the joint in adverse environmental effects is improved and the adhesive provides sealing to the joint. Weitzenböck and McGeorge [171] state that hybrid joints are also beneficial for multi-axial loads, in which each of the components is specifically designed for a load case. However, disassembly is almost impossible with hybrid joints.

In this thesis, bolted joints are studied for further development and investigation. The main driving force when it comes to studying bolted joints is their ease of use in on-site application and the potential for disassembly. This study is presented in the following chapter.

Table 4.1 Advantages and disadvantages of different joining techniques in FRP structures

Bolted joints	
Advantages	**Disadvantages**
• Disassembly is possible • Easy on-site application • Inspection is relatively simple • Tolerance to environmental effects • Ductile failure in case of bearing failure	• Poor structural efficiency due to stress concentrations at the holes • Increased joint weight • Low joint stiffness • Hole formation may cause damage to the laminate and strength degradation
Adhesively bonded joints	
Advantages	**Disadvantages**
• High strength-to-weight ratio • High fatigue resistance • High stiffness • Higher joint efficiencies than bolted joints • Corrosion resistant • Provide sealing	• On-site bond quality is difficult, requires surface preparation and high level of process control • Difficult inspection • Sensitive to peel and through-thickness stresses • Disassembly is almost impossible without component damage • Prone to environmental degradation • Catastrophic failure
Hybrid joints	
Advantages	**Disadvantages**
• Redundant, fail-safe joints • Reduced stress concentrations around the hole • Reduced sensitivity to peeling stresses	• Disassembly is almost impossible

5 Experimental and numerical investigation of bolted and bonded joints

5.1 Introduction

Bolted joints in FRP composites rely on the load being transferred through bearing between the shaft of the bolt and the connected laminates, unlike steel structures where the use of friction grip bolts is common and most of the load is transferred by frictional forces between the components. The load transfer by friction is made possible by pretensioning the bolts. In the design of composite bolted joints, the advantages of pretensioned bolts cannot be relied on, owing to the relaxation of the bolt tension over time because of the creep deformation in the FRP material. All advances offered by pretensioned bolts in terms of stiffness and strength are therefore disregarded in the design of bolted joints.

Bolt tension delays slip between the joined components, if clearances are present. Clearances are inevitable in bolted joints because of the ease of on-site assembly of bridge elements. The behaviour of a bolted joint with clearance and pretensioned bolt can be divided into several stages, as described by Stocchi *et al.* [172] and shown in Figure 5.1.

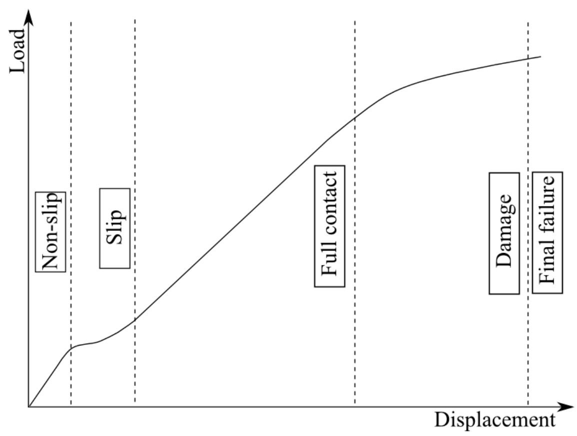


Figure 5.1 Illustration of different stages of load-displacement behaviour of bolted joints with clearances and pretensioned bolt (reproduced after [172])

The stiffness of the joint in the 'non-slip' stage depends essentially on the stiffness of the plates. The stage of slip begins when the maximum load that is only transferable by friction forces is exceeded. This load is dependent on the bolt tension that is provided and the coefficient of friction between the laminates. If a stable bolt tension and a high coefficient of friction between the plates are ensured, slip-resistant joints can be obtained in the service state of bridges.

In this study, an attempt is made to design bolted joints in which load transfer by friction is utilised and any slip in the joint is prevented in the serviceability limit state (SLS) of bridges. In order to account for the bolt tension relaxation due to the creep deformation of the material, steel inserts are utilised. The geometry of the used inserts is shown in Figure 5.2. The inserts were assembled in the hole of the laminates and full contact between the laminate and the insert surfaces was ensured.

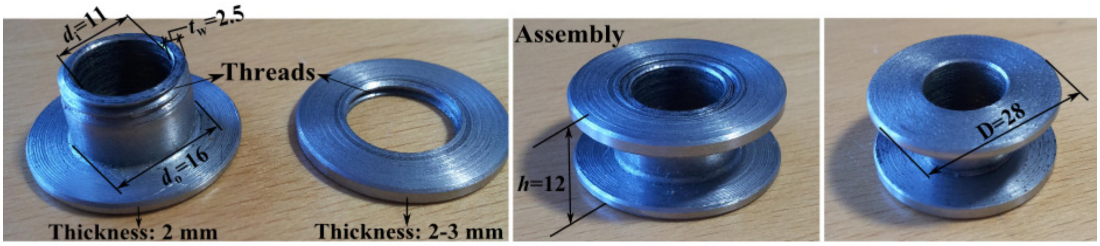


Figure 5.2 Configuration of steel inserts and their dimensions in mm (Paper V)

A series of experimental tests have been conducted to examine the behaviour, force-displacement relationship, the mechanism in relations to the load transfer of the proposed joints and the bolt tension relaxation in the joints. The main results and details on the joints and their behaviour can be found in Paper V.

This chapters summarises and adds to the information given in Paper V. The characterisation tests of the material used in the joints are described in detail in this chapter. Bearing tests and tests on adhesively bonded joints, not included in Paper V, are also described in this chapter.

5.2 Material characterisation tests

Most research on composite joints for civil engineering applications focuses on pultruded GFRP profiles. However, many bridges are built using structural elements that are manufactured with resin infusion, in which the fibre lay-up sequence is optimised, and they do not primarily have 0-degree rovings as pultruded elements do. Composite laminates fabricated with resin infusion were therefore chosen for this study. The composite material consisted of E-glass fibres and polyester as a matrix with a fabric lay-up of $[0/90, +/-45, 0/90, +/-45, \overline{0/90}]_S$ configuration. The properties of E-glass fibres and the resin are given in Table 5.1.

Table 5.1 Constituent material properties of the composite laminates

Property	Unit	E-glass	Polyester
Density	g/cm^3	2.54	1.09 *
Range of diameter	µm	3-20	--
Tensile strength	MPa	1724 - 2586	70
Tensile elastic modulus	GPa	72.4	3.8
Elongation at break	%	-	2.3
Coefficient of thermal expansion	$10^{-6}/^oC$	5.0	NA
Heat deflection temperature (HDT)[1]	^oC	-	85

*The property given at 23ºC

[1] Heat deflection temperature is the temperature at which the thermoplastic resin deforms under a specified load.

The thickness of the laminates varied between 7.0 and 7.5 mm. To determine some essential properties of the material, several coupon tests, based on the test methods of the ASTM standards, were conducted.

5.2.1 Tensile tests

The flat coupon test method, ASTM D3039-14 [173], was used to determine the tensile properties of the composite material. A total of six specimens, denoted as T1 to T6, were prepared. The dimensions and the test set-up for all the specimens are given in Figure 5.3. Each coupon was fitted with three strain gauges (gauge length of 3 mm), placed in the centre of the coupon, and an extensometer, as illustrated in Figure 5.3. In two test specimens, transverse strain gauges were placed to determine Poisson's ratio. The specimens were loaded at a displacement rate of 1 mm/min.

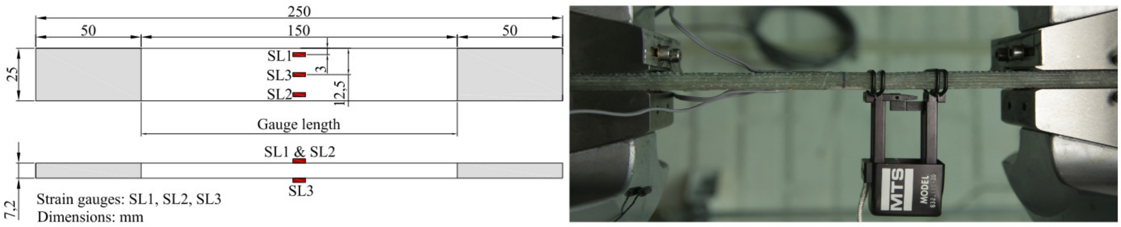


Figure 5.3 Dimensions and position of the strain gauges (on the left) and test set-up for tensile coupon tests (on the right)

The stress-strain behaviour of the material for all the specimens is given in Figure 5.4. The strain in Figure 5.4 represents either the strain reading from the extensometer or the average strain from the strain gauge readings (ε_{ave}), as in Equation (5.1), in which ε_{SL1}, ε_{SL2} and ε_{SL3} indicate the strains displayed by strain gauges SL1, SL2 and SL3, illustrated in Figure 5.3.

$$\varepsilon_{ave} = \frac{\frac{\varepsilon_{SL1} + \varepsilon_{SL2}}{2} + \varepsilon_{SL3}}{2} \tag{5.1}$$

The computed average strains were similar to the strain readings from the extensometer. The reason for using strain gauges in addition to the extensometer was to check any possible bending of the specimens during loading. Bending of the specimens was controlled and kept within the limits specified in the ASTM standard [173].

The mean curve in Figure 5.4 represents the average strain-stress relationship of the six tested tensile specimens. The results indicate that the material behaves non-linearly up to fracture. The tensile stiffness is substantially reduced at a strain of approximately 0.25%.

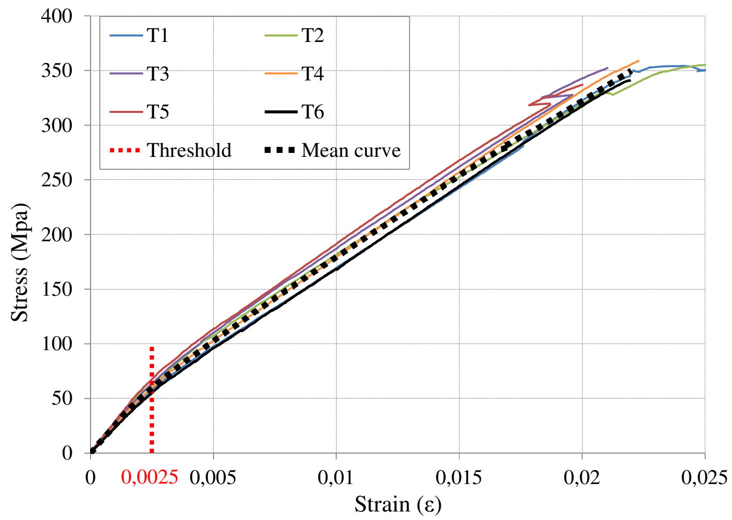


Figure 5.4 Stress-strain relationship of tensile tests on six specimens

To closely investigate the non-linear stress-strain behaviour of the composite material, one of the tensile specimens, namely T6, was tested under repeated loading and unloading. The specimen was loaded and unloaded four times to different load levels and then loaded to failure. The first four load-unload cycles are shown in Figure 5.5, in which unloading is presented by points A, B, C and D. In the first load cycle, the behaviour of the specimen is linear elastic. In the second load cycle, at a stress of 60 MPa, the slope of the curve changes. After this change of slope, the preceding load path is not traced back upon unloading. Unloading, at point B in Figure 5.5, takes place along a fairly straight line with a slope different from the initial slope and results in some residual strain. Upon reloading in the third load cycle, the slope follows the preceding unloading path and after point B the slope continues changing. The same behaviour is also observed for load 4, as seen in Figure 5.5. During loads 3 and 4 in the test, very small cracking sounds were heard.

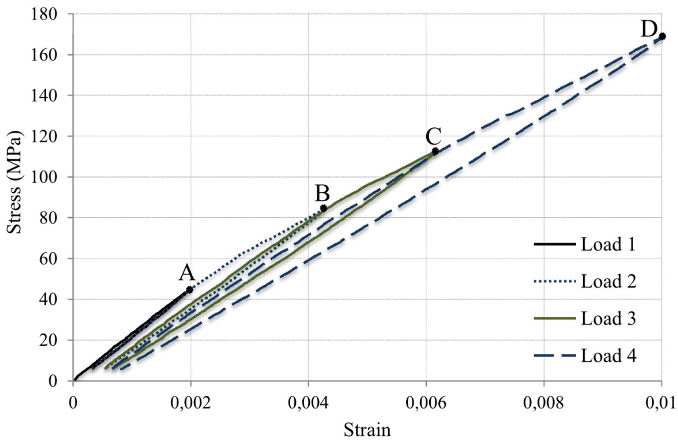


Figure 5.5 Tensile loading and unloading stress-strain results for specimen T6. Unloading started at points A, B, C and D.

This non-linear tensile behaviour of the material can be attributed to the cracking of the resin in the off-axis plies of the laminate (plies that are not parallel to the direction of the applied load) and eventual debonding between the resin and the fibres. It has been reported in the literature that resin cracking, which occurs at an early loading stage in the off-axis plies of the composite material, is the main source of stiffness change during the loading of composite laminates [174-178]. To illustrate this phenomena, a laminate consisting of three plies of 0- and 90-degree fibre orientations subjected to a tensile load in the longitudinal direction is shown in Figure 5.6. When the stress reaches a certain value, the 90-degree ply (referred to as off-axis ply and cracking ply) develops resin cracks along the fibres in the ply (the crack can also be in the form of fibre/resin debonding), which then grow through the resin up to the longitudinal fibres, as shown in Figure 5.6. These cracks develop at nearly uniform distances between one another until a certain load and then they remain stable on further loading [176, 179, 180]. The resin cracks induce stress relaxation locally in the vicinity of the cracks in the 90-degree ply, which in turn introduce non-uniform longitudinal strain in the adjacent plies (constraining plies) [178], as illustrated in Figure 5.6. The strain concentrations at the cracks cause the overall strain to be higher than the initial uniform strain ε_i for a given stress and this causes the stiffness loss.

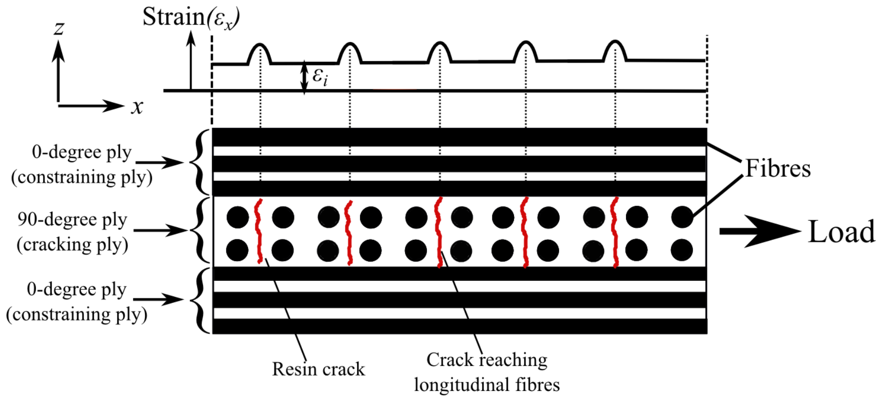


Figure 5.6 Illustration of an off-axis (90-degree) ply undergoing cracking and longitudinal strain distribution on the surface of the constraining ply

Talreja [178] related the development of cracks and thereby the deformation response to be dependent on the degree of constraint provided by the constraining plies. He provided a qualitative characterisation of the stress-strain response dependent on the degree of constraint for four cases: i) no constraint, ii) low constraint, iii) high constraint and iv) full constraint. The stress-strain response for these four cases is illustrated in Figure 5.7, where ε_{rc} denotes the strain at which resin cracking starts and ε_u the failure strain. The case of 'no constraint' in Figure 5.7(i) shows a linear-elastic response until the longitudinal strain reaches the strain at which resin cracking starts. The constraining plies, which provide no constraint in this case, are unable to carry the additional load imposed by the cracking plies and consequently extend instantaneously to failure. The 'no-constraint' case is an extreme case and is not common in FRP laminates. In the case of 'low constraint' in Figure 5.7(ii), when cracking initiates, multiple parallel cracks develop leading to an abrupt increase in strain and then further cracking requires an increasing load. This abrupt increase in strain is not observed for the 'high-constraint' case, but the initiation is cracking is represented by a knee in the stress-strain curve. In the case of full constrain in Figure 5.7(iv), the transverse cracking is fully suppressed and a linear-elastic response is observed.

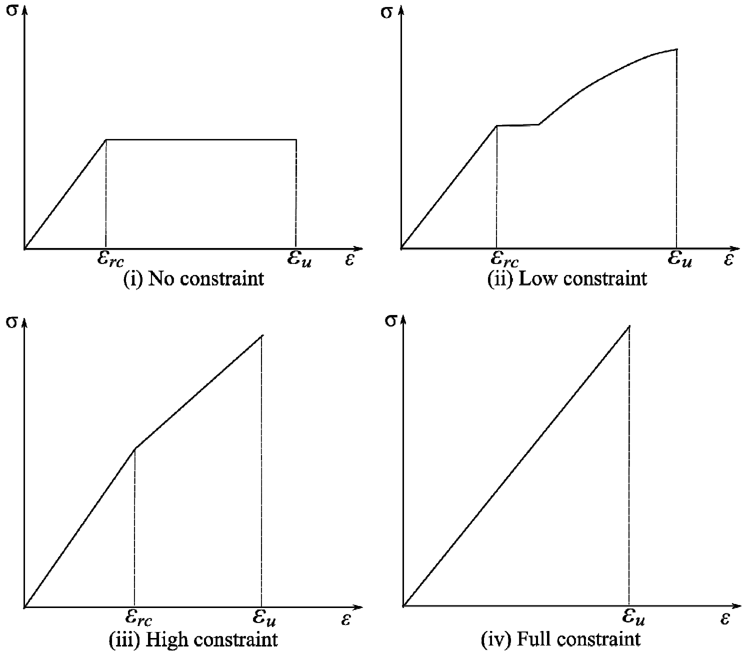


Figure 5.7 Schematic stress-strain diagrams for different constraint degrees according to Talreja [178]

The stress-strain behaviour of the composite material tested in this thesis is related to the response of the 'high-constraint' case in Figure 5.7. Garret and Bailey [179] report that the onset of resin micro-failure occurs between 0.2 to 0.5% strain for glass/polyester laminates. In this study, resin micro-cracking starts at 0.25%, as indicated in Figure 5.4, which falls within the range reported by Garret and Bailey. Owing to the non-linear stress-strain behaviour, two elasticity moduli were calculated for the material, in which elasticity modulus 1 corresponds to the first linear region of strain range 0-0.2% and elasticity modulus 2 corresponds to the second linear region of strain range 0.8%-1.5%, see Figure 5.4. A summary of the results is given in Table 5.2. The average values, standard deviation and the coefficient of variation were determined for each property. The reduction in the elasticity modulus is noted to be around 40%. In the literature, stiffness reduction due to resin micro-cracking up to 50 % have been found for different laminate configurations [175, 177, 179].

Table 5.2 Summary of measured tensile material properties

	Ultimate tensile strength [MPa]	**Ultimate tensile strain**	**Elasticity modulus 1 [GPa]**	**Elasticity modulus 2 [GPa]**	**Poisson's ratio**
Average	350.04	0.0224	25.834	14.920	0.225
Standard deviation	8.44	0.0020	2.193	0.606	-
Coefficient of variation	2.4%	9.1%	8.5%	4.1%	-

The final failure of all the specimens occurred in the gauge length, in which progressive delaminations and fibre breakage occurred. The typical failure mode, which is representative for all the specimens, is illustrated in Figure 5.8 for specimen T5.

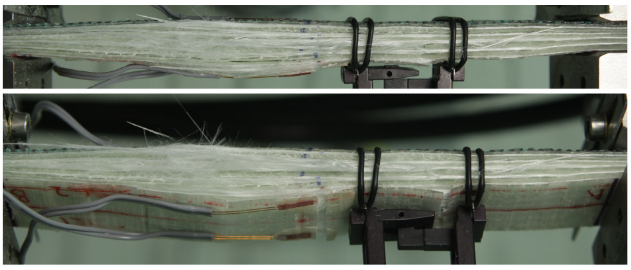


Figure 5.8 Failure mode of specimen T5 in tension

5.2.2 Compressive tests

To determine the compressive properties of the material, the ASTM D3410-03 standard [181] was followed. A total of five specimens, namely C1 to C5, were prepared and tested. The dimensions and the test set-up for all the specimens are given in Figure 5.9 and Figure 5.11. Each coupon was fitted with two strain gauges (gauge length of 3 mm), placed on each side in the centre of the coupon, as illustrated in Figure 5.9. The specimens were loaded at a displacement rate of 0.5 mm/min. The gauge length was larger than recommended in the standard (20 mm), due to machine limitations in the laboratory. However, this did not present any complications, as no buckling was observed in the specimens.

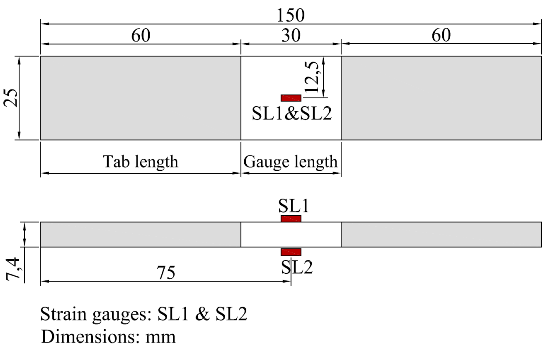


Figure 5.9 Geometry and instrumentation of compressive coupon tests

The stress-strain behaviour of the material for the five specimens is given in Figure 5.10. The compressive strain of each specimen represents the average strain readings from the SL1 and SL2 strain gauges. The results indicate that the material behaves linearly with slight non-linearity close to fracture.

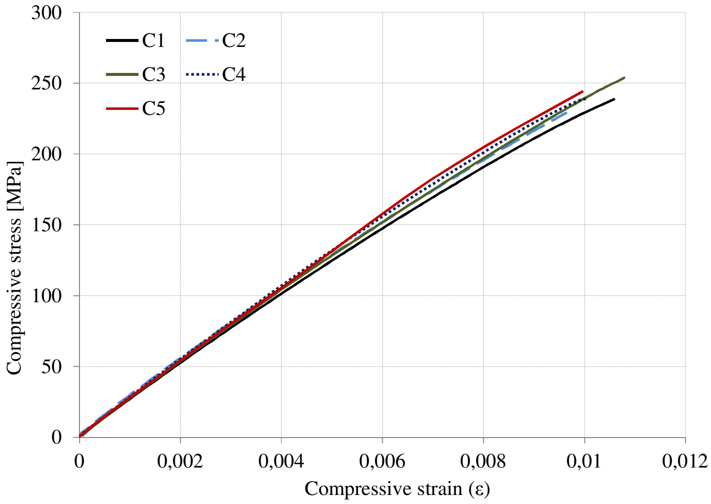


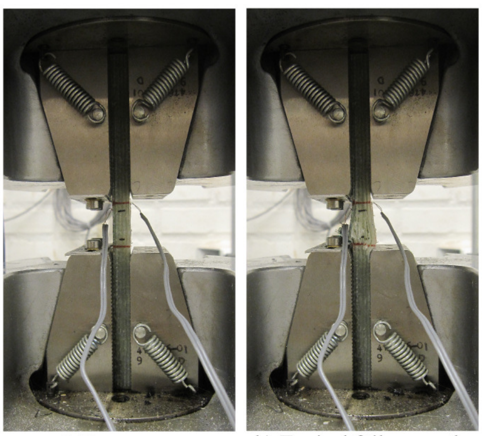
Figure 5.10 Compressive stress-strain curves of five specimens

A summary of the results is given in Table 5.3. The standard deviation and the coefficient of variation were determined for each property. The compressive elasticity modulus was calculated for the strain range of 0.1% to 0.3%, as recommended in the ASTM standard. The compressive elasticity modulus corresponds well to the elasticity modulus 1 determined in the tensile tests.

Table 5.3 Results of compressive coupon tests

	Ultimate strength (MPa)	**Ultimate strain**	**Elasticity modulus (GPa)**
Average	241.4	0.0102	25.647
Standard deviation	8.70	0.0005	0.454
Coefficient of variation	3.6%	4.6%	1.8%

The failure of all the specimens occurred at the gauge length in a brittle manner. The typical failure mode, representing all the specimens, is illustrated in Figure 5.11.



a) Test set-up b) Typical failure mode

Figure 5.11 Test set-up (a) and the typical failure of the compressive coupon tests (b)

5.2.3 In-plane shear tests

Five in-plane shear tests were carried out, based on the ASTM D7078 test standard [182], to determine the in-plane shear properties of the material. The dimensions of the coupons and the test set-up are shown in Figure 5.12. According to the standard, tensile loading is applied to the shear specimen to induce shear failure in the plane between the notches. To determine the state of shear strain, bi-axial ± 45° strain gauges were attached at the centre of the specimen. The specimens were loaded at a displacement rate of 0.25 mm/min.

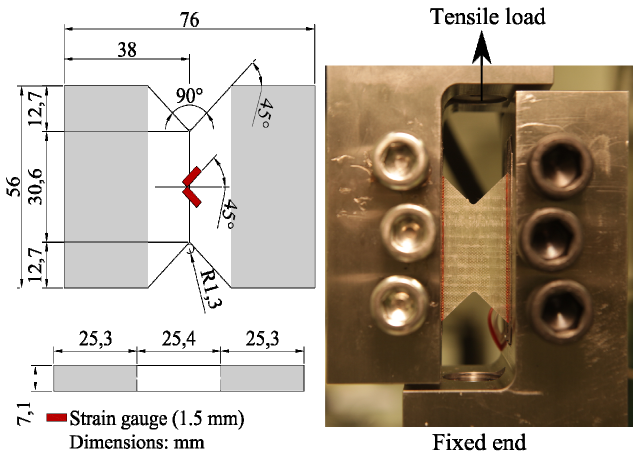


Figure 5.12 Shear coupon test dimensions, instrumentation with strain gauges (on the left) and test set-up (on the right)

The shear stress versus strain response is shown in Figure 5.13 for the five tested specimens, namely S1 to S5. The shear strain was computed as the sum of the absolute values of normal strains at +45° and -45° strain gauge, as in Equation (5.2).

$$\gamma_i = |\varepsilon_{+45}| + |\varepsilon_{-45}| \tag{5.2}$$

Only two of the specimens, namely S2 and S3, could be loaded to failure: The other specimens slipped in the grip areas because of insufficient clamping. The grey areas in Figure 5.12 represent the grip areas in the test specimens, which were fixed by torqueing the bolts.

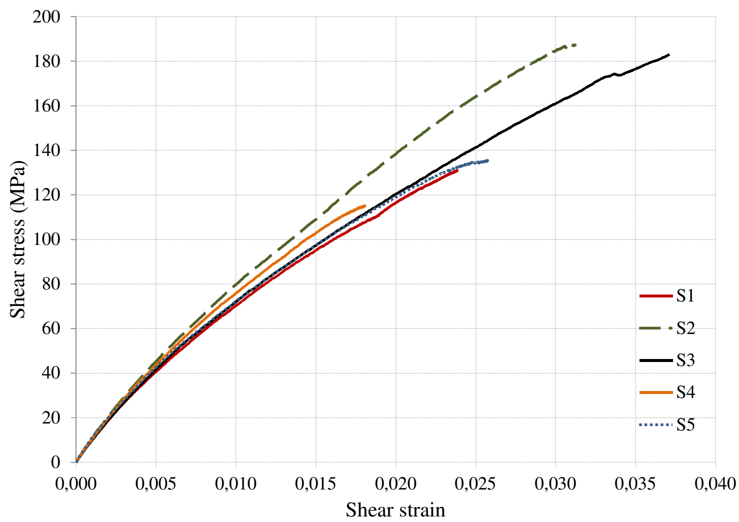


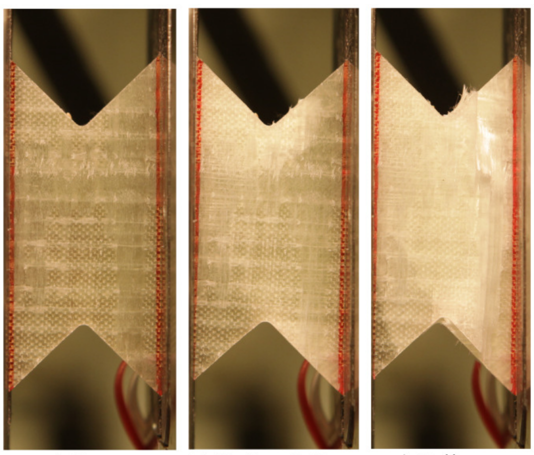
Figure 5.13 Shear stress-strain response of five tested in-plane shear specimens

The results of the in-plane shear tests are summarised in Table 5.4. The in-plane shear modulus was determined from the measured shear stresses and strains within the strain range of 0.15% to 0.4%, as recommended in the standard.

Table 5.4 Results of the in-plane shear tests for five specimens

	Ultimate shear strength (MPa)	**Ultimate shear strain**	**In-plane shear modulus (GPa)**
Average	185.2	0.0342	8.204
Standard deviation	-	-	0.420
Coefficient of variation	-	-	5.1%

In Figure 5.14, the failure of specimen S3 is shown. The failure occurred in the gauge area as a horizontal crack between the notches. The same failure mode also occurred for specimen S2.



a) Start b) Before failure c) Failure

Figure 5.14 Shear failure of specimen S3

5.3 Bolted and bonded joint tests

5.3.1 Introduction

An overview of the joint tests, their geometric parameters, the test set-up and the metallic inserts that were used can be found in Paper V. The tested joints were double-lap, single-bolted joints loaded in shear. The reason for testing joints with one bolt was to avoid the inclusion of parameters affecting the load distribution between bolts and to acquire a basic understanding of the load transfer mechanism for only one bolt. The joints were designed to promote bearing failure by following the guidelines and recommendations given in the ASTM test standard [183] and EuroComp [30].

In addition to the joint tests presented in Paper V, the bearing response of the material was tested following the ASTM D5961 standard [183] and it is presented in Section 5.3.2. The bearing tests were conducted to characterise the bearing response of the material and to investigate the effect of clearance. Moreover, double-lap, bonded joints were tested for comparison reasons. The results of the bonded joint tests are given in Section 5.3.4.

The experimentally investigated joints were also numerically modelled using the ABAQUS v6.13-3 FEA package. The purpose of the FE analysis was to promote a more meaningful interpretation of the experimental results. The main input data in the finite element modelling are given in Paper V.

5.3.2 Bearing tests

The bearing response of the material was tested for three different scenarios: (i) a bolt diameter of 10 mm (BS10), (ii) a bolt diameter of 10 mm and 1 mm clearance (BS11) and (iii) a bolt diameter of 16 mm (BS16). Three replicas for each type were tested. The test set-up was similar to the one described in Paper V, but the FRP laminate was mated with two steel plates, with a thickness of 6 mm, and loaded in double shear, see Figure 5.15. The smooth shank portion came into contact with the composite laminates. The bolts were loose-tightened in order to ignore any force transfer by friction in the contact surfaces.

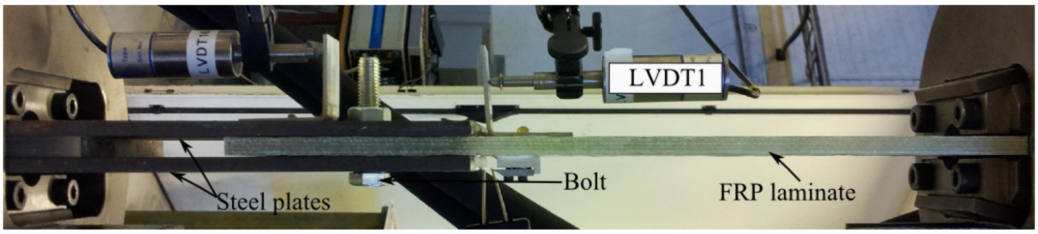


Figure 5.15 Test set-up for the bearing tests

The typical load-displacement curves of each test type are given in Figure 5.16 and Figure 5.17. The displacement represents the ones measured from LVDT1, depicted in Figure 5.15. The initial slip in BS10-3 in Figure 5.16(a) and BS16-3 in Figure 5.17, which were net-fit bolts, was due to unintended clearance between the hole and the bolt shank, because the bolt shanks were measured as 9.8 and 15.8 mm.

The load-displacement behaviour can be characterised as quasi-linear up to a noticeable and audible load drop, labelled as point A in the load-displacement curves in Figure 5.16 and Figure 5.17, which indicates an initial bearing failure, such as fibre micro-buckling, delaminations and/or the formation of shear cracks, as described in Section 4.1.2. In some tests, such as BS10-2, BS11-1 and BS16-1, the load drop is not distinct, but the initial damage is in form of a plateau. This difference might be due to some variation in the material around the hole or damage to the hole during drilling. In fact, some damage in the form of slight delaminations around the hole of the laminate for the BS16-1 specimen was observed before testing. Delamination or fibre pull-out around the hole are regarded as major problems when drilling the composites, adversely affecting the strength [184].

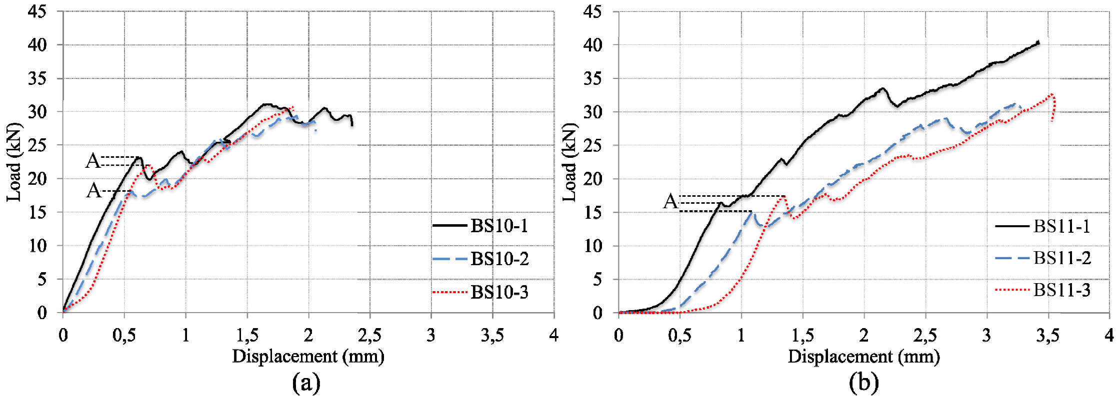


Figure 5.16 Bearing behaviour for: a) a bolt diameter of 10 mm (BS10), b) a bolt diameter of 10 mm and 1 mm clearance (BS11). Point A denotes damage initiation load.

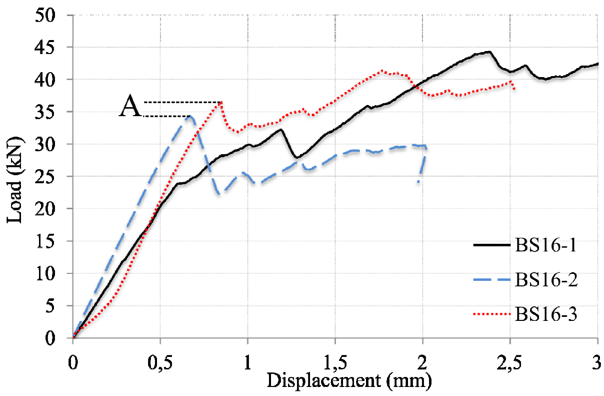


Figure 5.17 Bearing behaviour for a bolt diameter of 16 mm (BS16). Point A denotes the damage initiation load.

After the first load drop, the laminates are able to sustain an additional load (except BS16-2), which is more significant for the BS11 tests in Figure 5.16(b). This behaviour is fairly typical of joints with clearances in bearing, as it has already been observed in other tests reported in the literature [86, 104].

A summary of the bearing test results is given in Table 5.5. The damage initiation load in this thesis is referred to as the first load drop or the significant initiation of non-linearities in the bearing load-displacement curves. The bearing stresses are computed using Equation (5.3).

$$\sigma_{br} = \frac{F}{t * d} \qquad (5.3)$$

where F is the applied load, t is the laminate thickness, d is the bolt diameter.

According to the results presented in Table 5.5, the mean stiffness and damage initiation stress is lower for the joints with 1 mm clearance (BS11) compared with the non-clearance specimens (BS10). These findings indicate the adverse effect of the clearance and match existing results reported in the literature [56, 104, 185].

Table 5.5 Summary of the damage initiation load and stress of the joints and the bearing stiffness

Specimen ID	*Average damage initiation load (kN)*	*Average damage initiation stress (MPa)*	*Average stiffness (kN/mm)*
BS10	20.9	296.7	40.8
BS11	16.5	231.4	34.1
BS16	34.4	304.7	50.2

The bearing stresses for a joint with a bolt diameter of 10 mm without clearance and a clearance of 1 mm were studied numerically. In Figure 5.18, the radial bearing stresses at the mid-thickness of the laminate at a load level of 15 kN, the approximate load at which damage starts in the BS11 test, for the two cases is shown. The bearing stresses are uniformly distributed when no clearance is present, whereas they are fairly concentrated at the bolt-hole contact area in the case with clearance. The peak bearing stresses in the case with clearance are approximately 2.5 times higher than in the case with no clearance. These concentrated stresses can be an explanation of the failure initiation at lower loads and stiffness reduction for the joints with clearance.

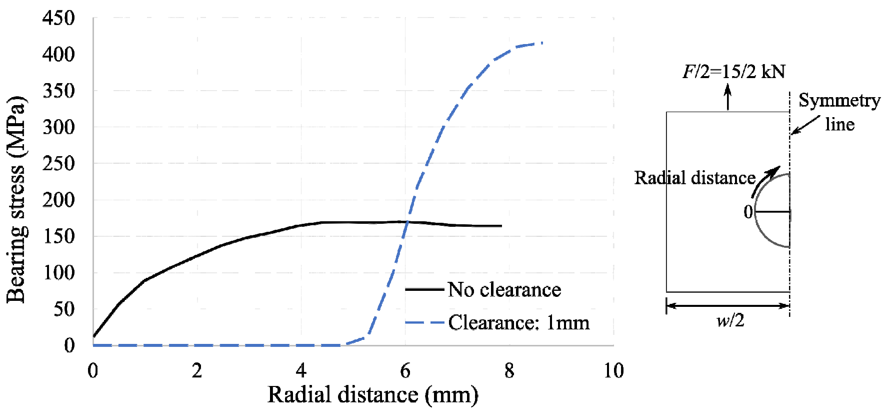


Figure 5.18 The radial bearing stress distribution for a joint with no clearance and a clearance of 1 mm

Comparing the results of the BS10 and BS16 tests in Table 5.5, the load and the initial stiffness of the BS16 tests are higher due to a larger bearing area. However, the damage initiation stresses are similar to one another. If the bearing stresses after the first loads drop are compared, as shown in Figure 5.19, the pattern of lower bearing stresses as the diameter increases can be seen. If the ultimate bearing stress were considered as the bearing strength, it could be claimed that the bearing strength decreases as the diameter increases. This is in agreement with some of the research results [58] discussed in Section 4.1.3. However, these tests are too few in number to draw any general conclusions.

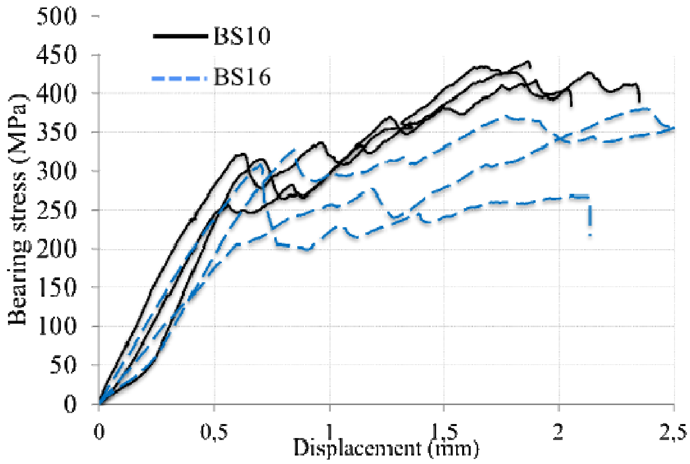


Figure 5.19 Bearing stress-displacement curves for BS10 and BS16 tests

The bearing failures of all the specimens were similar and are shown in Figure 5.20.

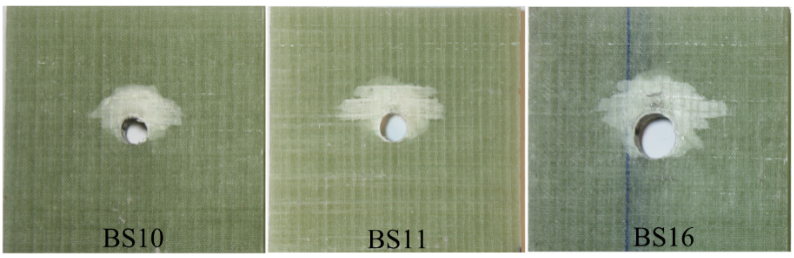


Figure 5.20 Bearing failure of BS10, BS11 and BS16 tests

5.3.3 Bolted joint tests

The specifications and the results of all the bolted joint tests are given in Paper V. The different types of tested joint included: i) conventional bolted joints, ii) bolted joints with inserts, iii) bolted joints with pretensioned bolts and iv) bolted joints with inserts and pretensioned bolts. All the joints had a clearance of 1 mm. In addition to these joint tests, bolt tension relaxation tests were conducted on joints with and without inserts. A summary and a comparison of the different joints are given in this section.

A comparison of the load-displacement curves between a conventional bolted joint and a bolted joint with inserts is shown in Figure 5.21. The curves indicate that the load at which damage is initiated is much higher for the bolted joint with inserts. An increase in the maximum load is also observed. The initial stiffness is similar for both joints, but, in the conventional bolted joint, the stiffness is significantly reduced after the initial bearing damage.

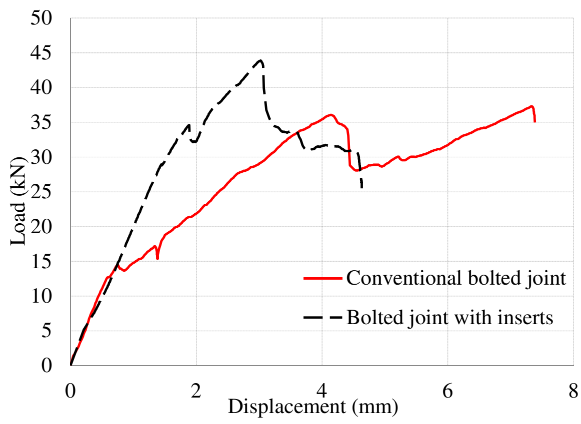


Figure 5.21 Load-displacement curves for a conventional bolted joint and a bolted joint with inserts (Paper V)

It should be recognised that the bearing area of the joints with inserts is higher, due to a larger hole diameter of 16 mm, compared with the conventional bolted joints that have a hole diameter of 11 mm. The maximum load that can be supported by the bolted joints with inserts is therefore expected to be higher. Comparing the load-displacement curve of the bolted joint with inserts with the bearing response of the bolted joints with a 16 mm diameter (BS16 tests presented in Section 5.3.2) in Figure 5.22, it can be seen that the initial damage starts at the same load level, around 35 kN. After initial damage, the bolted joint with inserts is able to resist an additional load in a stable manner compared with the bolted joint with an M16 bolt. This can be attributed to the confinement effect of the insert laps, which prevent through-thickness expansions of the laminate due to bearing and delay the damage until it splays outside the insert lap diameter (refer to Paper V). The stiffness differences between the bearing tests and the bolted joint with inserts in Figure 5.22 are due to the mating material in the bearing tests being steel plates, whereas the bolted joint with an insert is composed solely of FRP laminates.

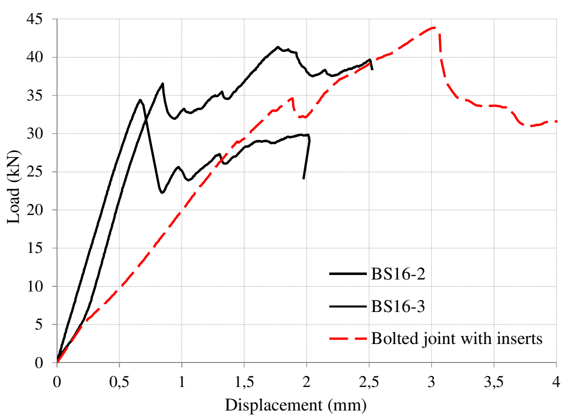


Figure 5.22 Comparison of the load-displacement curves of bolted joints with a bolt diameter of 16 mm (BS16) and bolted joint with a bolt diameter of 10 mm and inserts

It can be concluded that bolted joints with inserts are able to resist, in a stable manner, higher loads than bolted joints with an equivalent diameter, even though a clearance of 1 mm is present between the insert and the bolt.

The effect of pretensioned bolt on both conventional bolted joints and bolted joints with inserts was tested and is shown in Figure 5.24 and Figure 5.24. The treated insert represents the inserts with higher coefficients of friction between the insert surfaces due to a layer of tungsten carbide thermal sprayed onto the surfaces (see Paper V for more information).

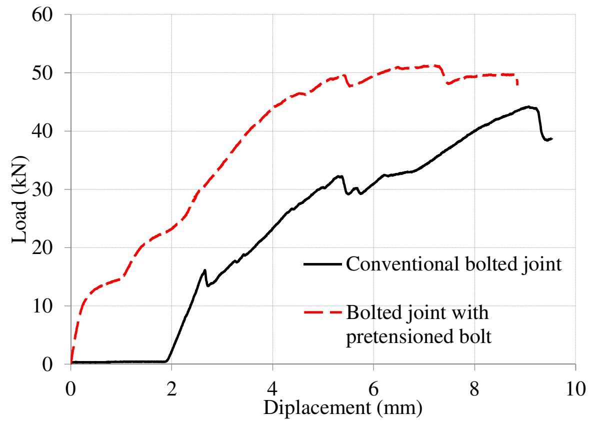


Figure 5.23 Effect of pretensioned bolt on conventional bolted joints

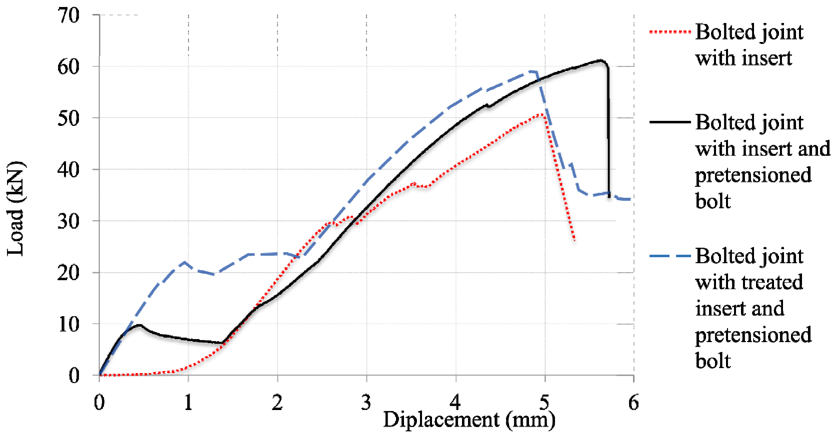


Figure 5.24 Effect of pretensioned bolt on bolted joints with inserts

In bolted joints with pretensioned bolt in Figure 5.23, the ultimate load is increased compared with the conventional bolted joints, as expected, due to the suppression of delamination. This does not hold true for bolted joints with inserts, because the bolt tension is accommodated by the inserts and not the laminate. The slight increase in the ultimate final load for the bolted joints with inserts and pretensioned bolts compared with the joint with inserts in Figure 5.24, is due to the load carried by additional kinetic friction forces. In this study, the main aim of pretensioning the bolt in joints with inserts was not to increase the final failure load but to be able to support the serviceability limit loads without any slip.

Depending on the coefficient of friction between the insert surfaces, the load carried by the joint before any slip, owing to the clearances, can be increased considerably in the serviceability limit state. This can be seen in Figure 5.24 by comparing the load-displacement curve of the bolted joint with insert and pretensioned bolt with the bolted joint with treated insert and pretensioned bolt.

Finally, a comparison of the load-displacement curves of the conventional bolted joint, bolted joint with inserts and bolted joint with treated inserts and pretensioned bolt is given in Figure 5.25.

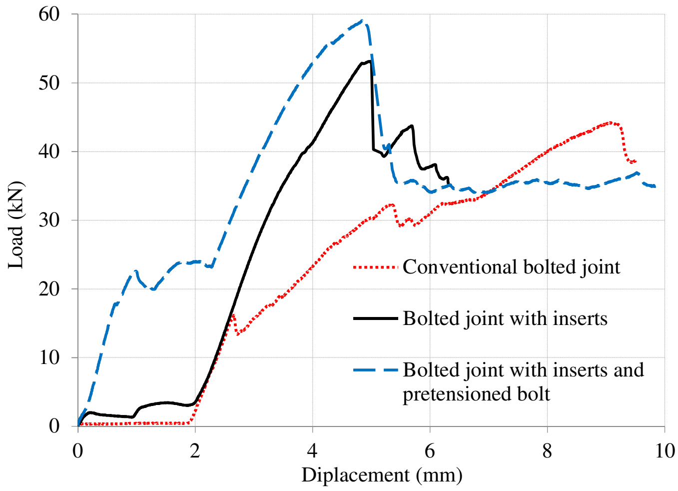


Figure 5.25 Comparison of the different tested joints (Paper V)

This comparison shows that the joint strength can be increased by using steel inserts and it is possible to carry substantial loads before any slip if the bolts are pretensioned.

Bolt-tension-relaxation tests conducted in bolted joints with and without inserts showed that bolt tension relaxation can be minimised by using inserts. In Figure 5.26 the results for the bolt-tension relaxation normalised to the initial bolt tension (P_{max} = 25 kN) are given. RBP1 and RBP2 represent the double-lap, bolted joints that were re-tightened after 24 hours, RBP3 and RBP4 represent the double-lap, bolted joints and RBIP1 and RBIP2 represent the double-lap, bolted joints with inserts.

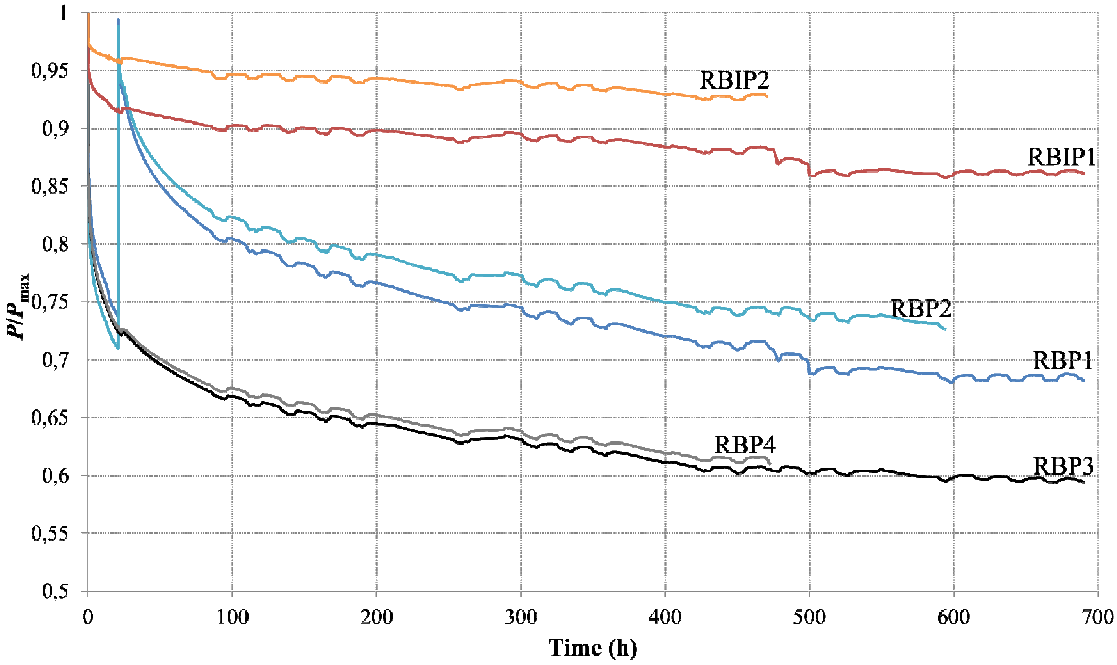


Figure 5.26 Measured bolt-tension relaxation normalised to the initial bolt tension for bolted joints with inserts (RBIP1-RBIP2) and bolted joints without inserts (RBP1-RBP4)

The results indicate approximately 40% relaxation in the bolt preload for room-temperature-dry conditions after 29 days in the bolted joints, RBP3 and RBP4. If the bolts are pretensioned again to the same initial bolt tension after 24 hours, joints RBP1 and RBP1, the relaxation is reduced to approximately 30%. As expected, the bolt-tension relaxation for the joints with inserts, RBIP1 and RBIP2, is much less and a maximum relaxation of around 15% is recorded. Additional discussion of these tests in given in Paper V.

5.3.4 Adhesively bonded joint tests

Three adhesively bonded, double-lap joints were tested for comparison with the bolted joints. The cold-cured, two-component epoxy resin, SikaDur330 adhesive type, was used to bond the laminates. This type of adhesive is commonly used in structural applications and it displays brittle behaviour. The mechanical properties of this adhesive have been tested by Keller and Vallee [150] in tension and compression (5 specimens each) and the results have been reported, as shown in Table 5.6. The results are presented as the mean value ± standard deviation.

Table 5.6 Tensile and compressive properties of epoxy SikaDur 330 adhesive [150]

Loading	Stress (MPa)	Strain (%)	E-modulus (GPa)
Tensile	38.1 ± 2.1	0.97 ± 0.13	4.6 ± 0.1
Compressive	80.7 ± 2.6	3.68 ± 0.08	3.1 ± 0.0

The joints were bonded in the laboratory and they were cured for ten days at the laboratory temperature (20ºC) before testing. The test set-up was the same as that of bolted joint tests presented in Paper V. The overlap between the laminates was 100 mm and the bond thickness was around 5 mm, see Figure 5.27. The load was applied in a displacement-controlled manner at a rate of 0.25 mm/min.

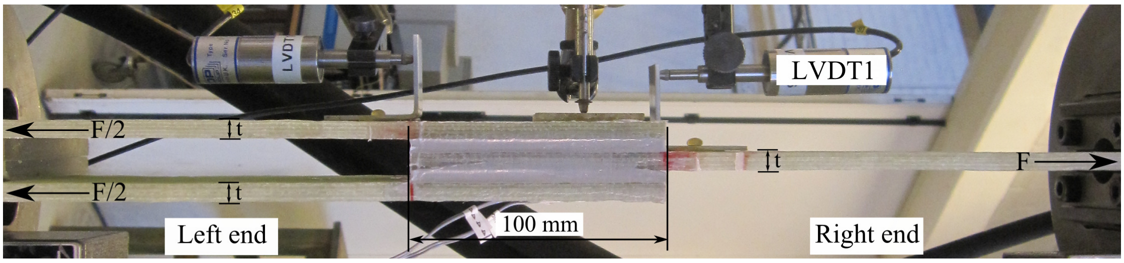


Figure 5.27 Configuration of bonded joints and test set-up

The load-diplacement responses of the three joints, designated as A1, A2 and A3, are shown in Figure 5.28. The displacement corresponds to the readings of LVDT1 shown in Figure 5.27.

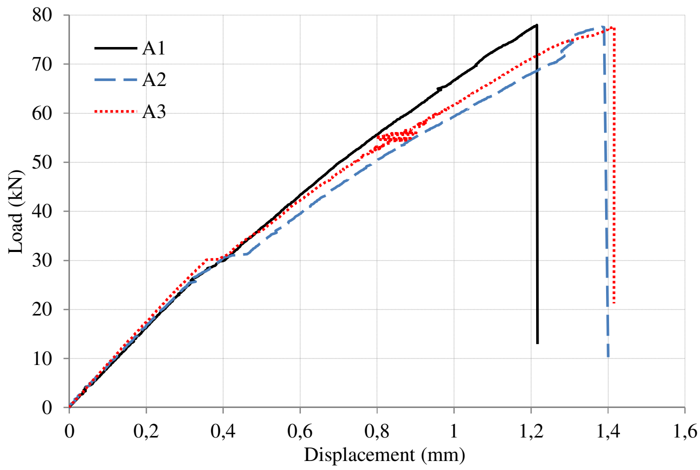


Figure 5.28 Load-diplacement response of bonded connections

Based on the load-diplacement response, the specimens clearly lose stiffness at a load level of 30 kN. During the execution of the tests, small cracking sounds were heard at this load level and they continued up to final fracture. The stiffness reduction could be attributed to the start of delamination in the centre laminate due to the through-thickness peeling stresses. The start of delamination and its propagation could be seen with naked eye at high load levels. In Figure 5.29, the delamination through the centre laminate just before failure for test specimen A3 is shown. This specimen is representative of the other test specimens. The final failure mode of the bonded joints was fibre-tear failure of the centre laminate.

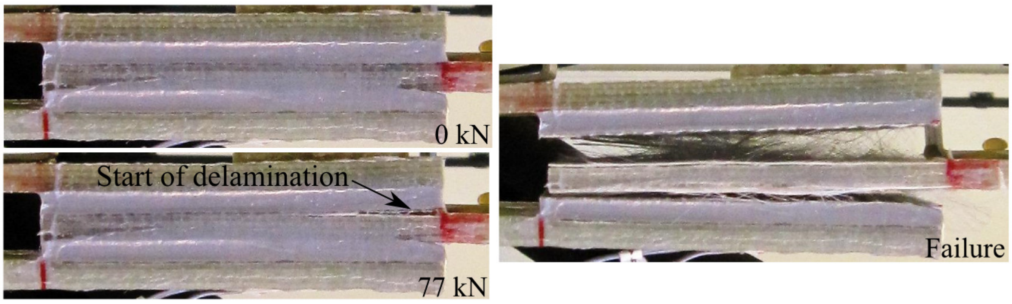


Figure 5.29 Illustration of delamination initiation and fibre-tear failure of A3 specimen

The delaminaton of the centre laminate started at the right bond end, as shown in Figure 5.29, due to the concetration of higher peeling and shear stresses compared with the left end of the bond line. This can be attributed to the stiffness imbalance in the right and left ends of the bonded specimen due to the same thickness of all the bonded laminates. The bonded joint therefore has lower stiffness in the right end, in which the thickenss is '*t*', as denoted in Figure 5.27, compared with the left end, in which the total thickness is '2*xt*'.

The concentration of peeling and shear stresses was further studied using the finite element method. The tested bonded joints were modelled using the ABAQUS v6.13-3 FEA package. The composite laminates were modelled with the same material input data as those used for the bolted joints, which are described in Paper V. The adhesive was modelled as an isotropic elastic material with an elasticity modulus of 4.5 GPa and a Poisson's ratio of 0.37 [186]. The modelled laminates and the adhesive bonds were merged together. Linear, eight-node brick (first-order hexahedral elements) elements with a reduced integration, C3D8R, were employed to mesh the joint. A fine mesh of 0.5 mm per element was used for the adhesive layers in order accurately to capture the stress concentrations at the bond line ends. The mesh element sizes varied from 0.5 mm in the bond line to 4 mm in the far outer regions for the laminates.

The stresses were examined at the interface of the bond at a load of 30 kN. In order to avoid the singularity stress points, the distance from the adhesive bond ends is kept at two elements, see Figure 5.30. The stress singularity issues and recommendations on how to deal with them are fully addressed in [149].

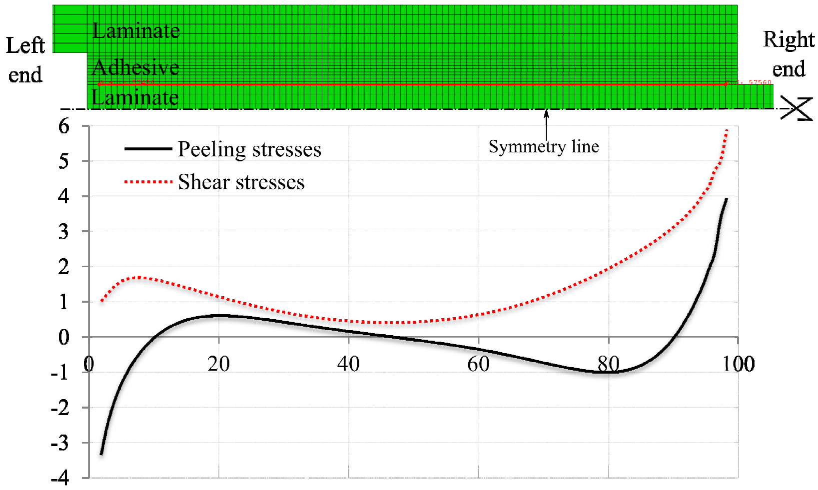


Figure 5.30 *Results for the finite element peeling and shear stresses at the bond interface*

As can be seen in Figure 5.30, higher peeling and shear stresses are recorded at the right end of the specimen. The combination of these peeling and shear stresses triggers delamination in the joint. The stiffness imbalance in the joint actually reduces the strength of the joint by loading the most critical end and unloading the less critical end.

The average stiffness of the bonded joints up to 30 kN and the average final strengths were 81.9 kN/mm and 77.6 kN. The maximum strength limit for these double-lap joints was set by the peeling stresses, rather than by the adhesive shear stresses, which complies with the theories for bonded joints with thick adherends.

5.3.5 Synopsis of joint tests

In Figure 5.31, the load-displacement curves for all the joint types are compared. It can be clearly seen that the stiffness and strength of the adhesively bonded joints is superior to that of the other types of bolted joint. However, bonded joints present their own challenges and disadvantages, which are discussed in Section 4.5, Paper I and Paper IV. On the other hand, it might not be completely fair to compare these two types of joint, because bonded joints cover a large area for joining members, as different from bolted joints, in which the loads are carried through a hole. Instead, the joint efficiencies of the joints are calculated and compared.

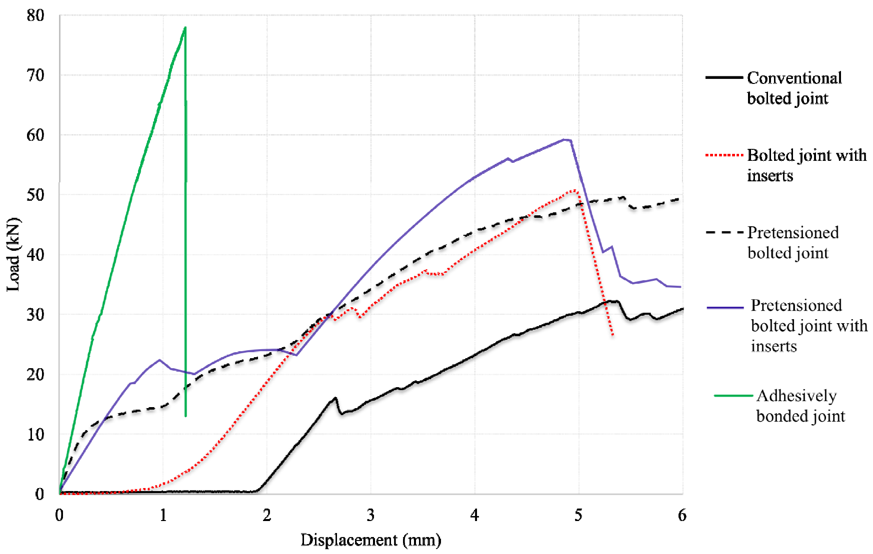


Figure 5.31 Summary of load-displacement curves for the various joints

Joint efficiency is defined as the percentage of the full strength of the connected parts that can be transmitted by the joint [127]. A common goal is therefore to provide a joint strength that is equal to the strength of the weaker joined part.

The strength of the laminate with the same dimensions as the joints, based on the tensile strength of the material, can be calculated as in Equation (5.4).

$$F_{u.lam} = \sigma_{tu} \times t \times w = 350 \times 7.2 \times 100 = 252kN \tag{5.4}$$

The net-section strength of the laminate for a 16 mm hole diameter is calculated as in Equation (5.5).

$$F_{u.net.lam} = \sigma_{tu} \times t \times (w - d_h) = 350 \times 7.2 \times (100 - 16) = 211.68kN \tag{5.5}$$

where σ_{tu} is the ultimate tensile strength of the laminate, t is the laminate thickness, w is the laminate width and d_h is the hole diameter.

The tensile strength of the laminates with a hole is lower than the net-section strength due to the orthotropic and brittle behaviour of the material. Lopez-Anido [187] suggested further reducing the net-section strength by a factor k. The value of k was suggested as 0.7 for pultruded sections loaded in the longitudinal direction and this value was further supported by Cunningham *et al.* [188]. The open-hole reduction factor of 0.7 is used in this study to calculate the open-hole strength of the laminate, even though the laminate is not pultruded, due to lack of data. The tensile strength of the open-hole laminate is reduced to 148.2 kN, according to Equation (5.6).

$$F_{u.oh} = k \times F_{u.net.lam} = 0.7 \times 211.68 = 148.2kN \tag{5.6}$$

The joint efficiencies of the adhesively bonded joint and the pretensioned bolted joint with inserts are calculated using Equations (5.7) and (5.8), respectively.

$$u_A = \frac{F_{u.A}}{F_{u.lam}} \times 100 = \frac{77.6}{252} \times 100 = 30.8\% \tag{5.7}$$

$$u_{BIP} = \frac{F_{u.BIP}}{F_{u.net.lam}} \times 100 = \frac{61}{148.2} \times 100 = 41.2\% \qquad (5.8)$$

where $F_{u.A}$ represents the strength of the bonded joint and $F_{u.BIP}$ represents the strength of the pretensioned bolted joint with inserts.

The results indicate that the bolted joints with inserts and preload could have higher joint efficiency than the bonded joints. The bonded joint reaches a maximum joint efficiency of 31%, while the pretensioned bolted joint with inserts has the potential to achieve a higher efficiency of 41%. These joint efficiencies are low, but they are fairly common in composite joints, as described in Section 4.1.3.

5.4 Summary

A design of bolted joints for FRP bridge structures that do not suffer, when clearance is present, from slip under service loading was proposed (Objective 5). The design includes the use of metal inserts in the bolt holes of the composite laminates. Experimental and numerical analyses were carried out on single-bolted, double-lap joints loaded in shear. The main findings of these studies, which are mainly presented in Paper V and findings and reflections associated with Section 5 are as follows.

- The tensile stress-strain behaviour of the composite material in this study was non-linear due to failure in the off-axis plies, resulting in 40% reduction in the elasticity modulus at an early loading stage.

- This study confirms the adverse effect of clearance on the stiffness and damage initiation load in bolted composite joints. For a clearance of 1 mm, the stiffness and the damage initiation load were reduced by 24% and 21% respectively, compared with a joint without clearance.

- An increase in bolt diameter had a tendency to cause a decrease in bearing strength. However, additional testing is required to support this observation.

- The metallic inserts with laps can delay the damage of the FRP laminate around the hole, due to the confinement effect of the insert laps, which prevent through-thickness expansion in the FRP laminate. The inserts can spread the radial bearing stresses to the laminates, which results in the reduction of high stress concentrations in the bearing plane of the laminate.

- The initial damage visible in the load-displacement curves in bolted joints with pretensioned bolts was approximately 2.5 times higher than the conventional bolted joints. This can be attributed to the suppression of delamination damage in the laminates when the bolts are pretensioned. Bolted joints with pretensioned bolts failed at 16% higher maximum loads than the conventional bolted joints. The ultimate maximum failure load in the conventional bolted joints was recorded at displacements almost double those of the bolted joints with pretensioned bolts.

- An increase in the initial damage load of approximately 48% is observed for bolted joints with inserts and pretensioned bolts compared with bolted joints with inserts. The pretensioned bolts intensify the confinement effect of insert laps, thus delaying the damage initiation in the FRP laminate. Bolted joints with inserts failed at around 14% higher loads that pretensioned bolted joints with inserts. The slight increase in the ultimate final load can be attributed to the additional load carried by kinetic friction forces.

- The bolt-tension relaxation was fairly significant in conventional bolted joints due to the creep deformation of the composite material. A bolt tension loss of 40% was recorded for the conventional bolted joints after 29 days for room-temperature-dry conditions. Even if the bolts were re-tightened to the initial bolt tension after 24 hours, the bolt-tension loss was still significant (up to 30%). The bolt-tension relaxation could be considerably reduced by using steel inserts in bolted joints, because the bolt tension is supported by the inserts. A maximum bolt-tension loss of 15% was recorded for the bolted joints with inserts. Bolt-tension-relaxation tests for a longer period of time than that used in this study are necessary.

- The stiffness prior to slip in the pretensioned bolted joints was higher than that of the pretensioned bolted joints with inserts, due to differences in the load-transfer mechanisms. In pretensioned bolted joints, the loads are only transferred by frictional forces and only the extension of the material during loading is included in the load-displacement curves. In pretensioned bolted joints with inserts, the loads are transferred partly through bearing to the laminate and partly through friction forces. As a result, the displacement in the load-displacement curves includes the extension of the material and the displacement due to bearing, leading to higher total displacements and thereby lower stiffness. On the other hand, the stiffness of these joints is approximately 50% higher than that of the bolted joints with or without inserts.

- Bolted joints with inserts show potential when it comes to providing slip-resistant joints. The load that can be carried prior to slip depends on the coefficient of friction between the insert lap surfaces and the provided bolt tension. The bolt-tension losses can be fairly significant prior to slip in the statically loaded joints. This should be taken into account in the design of joints when the bolt tension is accounted for.

6 Conclusions

6.1 General conclusions

The application of FRP materials in bridges, their economic and environmental feasibility and connections that facilitate the application of these materials have been investigated in this thesis. The scope of the work was divided to address five specific objectives as presented in the introduction. The general conclusions pertaining to these objectives are summarised in this section. The conclusions also refer to Papers I-V appended to this thesis.

The structural and in-service performance of fibre reinforced polymer bridge decks was reviewed to present the current knowledge status and identify possible knowledge gaps (Objective 1, Paper I). The review highlighted the advantages of FRP decks, such as their high specific stiffness and strength, their corrosion and high fatigue resistance, their potential for rapid installation and increased safety. Despite the advantages, due to their relatively new use in bridge constructions, there are still potential areas for investigation. The main areas which should be addressed, based on the outcome of Paper I, include:

- The standardisation of experimental test methods, design practices and criteria and the development of design codes
- The development of appropriate wear surfaces for application to FRP decks. The cracking and debonding of the wear surfaces have been reported as a common problem in existing bridges with FRP decks
- Long-term durability data are required for FRP decks under realistic fatigue loads and environmental conditions
- Comparative studies of the cost and environmental impact of various bridge designs, including bridges with FRP decks, over the service life of the bridge, are necessary
- The development of joining techniques for FRP decks and bridge members which enable swift on-site assembly and disassembly

The last two identified research areas were chosen for further research in this thesis.

A detailed assessment of the life-cycle cost and the environmental impact in terms of carbon emissions related to a case-study bridge was conducted (Objective 2, Paper II). The total replacement of a steel-concrete bridge was compared with a bridge rehabilitation scenario in which the concrete deck was replaced by an FRP deck. The results indicated that the scenario of the replacement of the deteriorated concrete deck with an FRP deck yields fewer life-cycle costs and carbon emissions, 31% and 20% respectively, than the replacement of the bridge with a new steel-concrete bridge. In addition, the increase in average daily traffic (ADT) passing the bridge significantly influences both the cost and the carbon emission results, which is in turn favourable for the FRP deck alternative thanks to its rapid installation. Additional life-cycle cost analyses and life-cycle assessments are suggested for bridges with FRP decks in different conditions. For example, life-cycle assessments including environmental impacts other than carbon emissions are necessary. Due to sparse and limited input data for both life-cycle cost and life-cycle assessments, the development of internationally-accepted databases is necessary.

A novel panel-level connection for FRP decks was designed conceptually and the structural behaviour was investigated numerically and experimentally (Objective 3, Papers III and IV). The connection was designed through collaboration between the designer, client, manufacturer and contractor. Interest focused on the development of a connection concept providing swift on-site assembly. The developed connection was based on the mechanical interlocking of the two modules, consisting of a tongue-and-groove mechanism, sliding into one another at an angle of 45°. The developed connection was efficient with regard to rapid installation. However, the method of manufacturing the connection modules in this study, namely the vacuum infusion method, was not efficient and geometric flaws resulted in the connection modules. The performance of the connection modules in the serviceability limit state was therefore jeopardised. In the experimental tests, deflection inconsistencies were observed at the top flanges of the connection modules and they could pose a risk of wear surface cracking. No formulation of deflection limits based on the prevention of wear surface cracking is available. Additional tests with specimens with accurate fit and an applied wear surface are necessary to reach conclusive statements for the serviceability limit state performance of the connection module. The load-carrying capacity of the tested specimen was higher than 433 kN, which is more than twice the ultimate limit state load (202.5 kN). Pseudo-ductile behaviour was observed from the load-deflection curve. The results of this study showed that the proposed connection has real potential for use in FRP decks. Additional tests of the fatigue performance and the environmental effects on the durability of the connections are suggested.

The joining techniques between FRP members were reviewed, with special attention being paid to plate-to-plate, bolted joints (Objective 4). The main parameters influencing the performance of the bolted joints were characterised and are summarised as follows.

- In the lay-up composition of the composite material, fibre orientation plays a significant role in terms of the behaviour and strength of the joint, whereas the stacking sequence has only a slight influence. Plies of 0-degrees are necessary to maximise the strength of the joint, but it is important not to stack them at the surface of the laminates due to premature failure as a result of buckling and splitting.

- The pretensioned bolts can increase the joint bearing strength. However, the initial bolt tension is relaxed owing to the creep deformation of the composite laminate and it is therefore not considered in the design of joints.

- Clearances between the bolts and bolt holes have an adverse effect on the stiffness and damage initiation load of bolted joints.

- The geometric parameters directly influence the failure mode and strength of bolted joints. A large part of the experimental data found in the literature is presented in terms of joint capacity as a function of joint geometry parameters and these parameters are essentially established to achieve a specific failure mode.

The majority of the research focuses on the strength of the joints and less on the stiffness. Due to the importance of the stiffness requirements in bridges, one objective of this study was to develop slip-resistant joints applicable to FRP bridge elements, which enable rapid on-site assembly and disassembly, and to assess their structural performance experimentally and numerically (Objective 5, Paper V). This objective was realised by designing bolted joints with metallic inserts, in which the bolts are pretensioned and clearances may be present. Clearances are needed to facilitate on-site assembly. Metallic inserts are necessary to address the issue of bolt-tension relaxation. Experimental and numerical analyses were performed to study the performance of bolted joints with inserts, pretensioned bolts and clearances. The experimental tests included single-bolted, double-lap joints loaded in shear. The results indicated that bolted joints with inserts and pretensioned bolts have the potential to achieve slip-resistant joints in the service state of bridges. The load, which can be taken without slip, is dependent on the coefficient of friction between the insert lap surfaces and the provided initial bolt tension. In this study, a maximum average load of 21 kN was achieved for a single-bolted, double-lap shear joint prior to slip. The average coefficient of friction between the inserts was 0.5 and the initial bolt tension was 25 kN. The bolt-tension relaxation due to the creep deformation of the composite material was minimised by the use of the metallic insert. Bolt-tension-relaxation tests for a period of 29 days revealed that the loss of bolt preload for a joint with and without inserts is 15% and 40% respectively. However, the experimental joint tests demonstrated that the bolt load can vary substantially during static loading before any slip. Attention should be paid to the loss of bolt tension in the design of these joints for the service state of bridges. The efficiency of the joints with inserts and pretensioned bolts was increased compared with the simple conventional bolted joints in terms of strength and stiffness. Additional tests are required for these types of joint to further validate their static behaviour and to assess their fatigue and durability properties.

6.2 Suggestions for further research

One of the main concerns usually expressed by the authorities when it comes to the use of FRP members in bridges is the long-term performance. At present, our knowledge of the long-term behaviour of FRP bridge elements and their connections is limited. The oldest road bridge with an FRP deck that has been monitored for a period of time dates back to 1996, No Name Creek Bridge in Kansas, USA. As a result, the in-service performance of FRP decks has been known for fewer than 20 years. Long-term durability data are required to support the claims that FRP materials have enhanced durability properties compared with traditional materials in the long term. Further monitoring of in-service bridges with FRP members is therefore strongly recommended. Today, the design of FRP bridges is performed by applying large partial safety factors to account for uncertainties in the durability of the material. It goes without saying that it is not only the long-term performance of the FRP material but also of the joints which is important. Testing the durability properties of the proposed joints in this thesis was outside the scope of this thesis, but it is recommended for further research.

The loading of structures in reality is multi-axial. The experimental tests performed so far include only one-directional loading, but this is far from representative of the range of working conditions for composite bolted joints in bridges. Despite being difficult and expensive, the testing of joints considering any interaction of loads, for example, joints under shear and tension simultaneously, is necessary. In addition, the study of joints under thermal effects is suggested. The design of joints should allow for movements due to thermal effects. Research is therefore necessary to quantify these effects and set requirements for the design of composite joints under thermal loads.

Finite element analyses are fairly convenient when it comes to studying the behaviour of structures or details such as connections. These analyses offer an opportunity to obtain a deeper understanding of the performance of structures and reveal data which are sometimes impossible to obtain in a test. Finite element analyses were employed in the study of the joints in this thesis. However, the composite FRP material was modelled as an orthotropic, linear-elastic material and any progressive material damage was not included. As observed in the tensile coupon material tests, the behaviour of the material is not completely linear. In order to capture the non-linearity and damage in the FRP material, the laminates can be modelled using progressive-damage models, implementing different failure criteria. In this way, the behaviour of the joints can be captured and calibrated to the tests. Once calibration is complete, parametric studies to check the influence of different parameters can be conducted, thereby saving money and time in performing a large number of tests. For this reason, the development of finite element models including material-damage models is recommended for further studies.

References

1. Hobbs D W. Concrete deterioration: Causes, diagnosis, and minimising risk. *International Materials Reviews*, 2001; 46(3): p. 117-144.

2. Wallbank E. The performance of concrete in bridges. A survey of 200 highway bridges. London, England, 1989.

3. Harryson P. Innovative procurement resulting in a novel frp bridge. In: *The 7th International Conference on FRP Composites in Civil Engineering (CICE2014)*, Vancouver, Canada, 2014. International Institute for FRP in Construction (IIFC).

4. Harryson P. Industrial Bridge Engineering - Structural developments for more efficient bridge construction, in *Department of Civil and Environmental Engineering*. 2008, Chalmers Unversity of Technology: Göteborg, Sweden.

5. Khan M A. Accelerated Bridge Construction: Best Practices and Techniques. Boston: Butterworth-Heinemann, 2015, p. 656.

6. GangaRao H. 33 - Infrastructure Applications of Fiber-Reinforced Polymer Composites, in *Applied Plastics Engineering Handbook*, M. Kutz, Editor. 2011, William Andrew Publishing: Oxford. p. 565-584.

7. Zoghi M. The International Handbook of FRP Composites in Civil Engineering. Hoboken: CRC Press, 2013.

8. Foster D C, Richards D, Bogner B R. Design and installation of fiber-reinforced polymer composite bridge. *Journal of Composites for Construction*, 2000; 4(1): p. 33-37.

9. Clapham P, Canning L, Asiedu K. The reconstruction of Moss Canal Bridge, Rochdale, UK. *Proceedings of the Institution of Civil Engineers: Bridge Engineering*, 2015; 168(1): p. 64-75.

10. Wasielewski J, Nicoll B, Hilaire S S. Rehabilitation of the Rocks Village Bridge. In: *Structures Congress 2014*, 2014. ASCE.

11. Veltkamp M, Peeters J. Hybrid bridge structure composed of fibre reinforced polymers and steel. *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, 2014; 24(3): p. 425-427.

12. Oppe M W, Knippers J. Application of bolted connections in fibre-reinforced polymers. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 2011; 164(5): p. 321-332.

13. Keller T. Use of Fibre Reinforced Polymers in Bridge Construction. Zurich, Switzerland: IABSE-AIPC-IVBH, 2003.

14. Bansal A, Cano J F M, Munoz B O O, Paulotto C. Examples of applications of fibre reinforced plastic materials in infrastructure in Spain. *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, 2010; 20(4): p. 414-417.

15. Hurtado M A, Bansal A, Paulotto C, Primi S. FRP girder bridges: Lessons learned in Spain in the last decade. In: *Conference on FRP Composites in Civil*

Engineering (CICE), Rome, Italy, 2012. International Institute for FRP in Construction (IIFC).

16. Bank L C. Application of FRP Composites to Bridges in the USA. In: *International Colloquium on Application of FRP to Bridges*, Tokyo, Japan, 2006. Japan Society of Civil Engineers (JSCE).
17. Fam A, Pando M, Filz G, Rizkalla S. Precast piles for route 40 bridge in Virginia using concrete filled FRP tubes. *PCI Journal*, 2003; 48(3): p. 32-45.
18. Bottenberg R D. Fiber-reinforced polymer decks for movable bridges. *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, 2010; 20(4): p. 418-422.
19. Lewis A E, Dumlao C, Lee M J, Weinmann T L. Performance of Schuyler Heim composite Bridge deck replacement port of Los Angeles, California. 2004, Transportation Research Record. p. 36-46.
20. Sams M. Broadway bridge case study bridge deck application of fiber-reinforced polymer. In: *Transportation Research Board - 6th International Bridge Engineering Conference: Reliability, Security, and Sustainability in Bridge Engineering*, Boston, United States, 2005.
21. Yang J, Kalabuchova L. Application of FRP materials in culvert road bridges: A feasibility study with focus on mechanical behavior and life-cycle cost analysis in *Department of Civil and Environmental Engineering*. 2014, Chalmers University of Technology: Sweden.
22. Haghani R. Needs for maintenance and refurbishment of bridges in urban environments. 2013, PANTURA. p. 148.
23. Zureick A H, Shih B, Munley E. Fiber-reinforced polymeric bridge decks. *Structural Engineering Review*, 1995; 7(3): p. 257-266.
24. Agarwal B D, Broutman L J, Chandrashekhara K. Analysis and Performance of Fiber Composites. John Wiley & Sons, 2006, 2006, p. 562.
25. Domone P, Illston J. Construction Materials: Their Nature and Behaviour, Fourth Edition. Taylor & Francis, 2010.
26. Keller T, Rothe J, De Castro J, Osei-Antwi M. GFRP-balsa sandwich bridge deck: Concept, design, and experimental validation. *Journal of Composites for Construction*, 2014; 18(2).
27. Camata G, Shing B. Evaluation of GFRP honeycomb beams for the O'Fallon Park bridge. *Journal of Composites for Construction*, 2005; 9(6): p. 545-555.
28. Åström B T. Manufacturing of polymer composites. London, UK: Chapman & Hall, 1997.
29. Mazumdar S. Composites Manufacturing: Materials, Product, and Process Engineering. Boca Raton, Florida: Taylor & Francis, 2001.
30. Clarke J L. Structural Design of Polymer Composites: Eurocomp Design Code and Background Document. London, UK: Taylor & Francis, 2003.
31. BD90/05. Design of FRP Bridges and Highway Structures. *UK: Highway Agency*, 2005.

32. CUR96: CUR Recommendation 96: Fibre Reinforced Polymers in Civil Load Bearing Structures*,* 2003. CUR, Amterdam, The Netherlands.

33. CNR-DT205/2007: Guide for the Design and Construction of Structures made of Pultruded FRP elements*,* 2008. Italian National Research Council (CNR), Rome, Italy.

34. ACMA. Pre–Standard for Load and Resistance Factor Design of Pultruded Fiber Polymer Structures. *American Composites Manufacturer Association*, 2010.

35. CEN: Reinforced Plastic Composites: Specifications for Pultruded Profiles Parts 1–3 EN 13706*,* 2002. European Committee for Standardization (CEN), Brussels, Belgium.

36. Finnveden G, Hauschild M Z, Ekvall T, Guinée J*, et al.* Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 2009; 91(1): p. 1-21.

37. . ETSI PROJECT (Stage 1): Bridge Life Cycle Optimisation, J. A. and S. H., Editors. 2007, Helsinki University of Technology: Espoo, Finland.

38. Russell A, Ekvall T, Baumann H. Life cycle assessment - Introduction and overview. *Journal of Cleaner Production*, 2005; 13(13-14): p. 1207-1210.

39. Glass J, Dyer T, Georgopoulos C, Goodier C*, et al.* Future use of life-cycle assessment In Civil Engineering. *Proceedings of Institution of Civil Engineers: Construction Materials*, 2013; 166(4): p. 204-212.

40. Safi M A E-F. LCC Applications for Bridges and Integration with BMS, in *Civil and Architectural Engineering*. 2012, Royal Institute of Technology: Sweden.

41. Du G, Karoumi R. Life cycle assessment framework for railway bridges: Literature survey and critical issues. *Structure and Infrastructure Engineering*, 2014; 10(3): p. 277-294.

42. Mara V. Fibre reinforced polymer bridge decks: Sustainability and a novel panel-level connection, in *Department of Civil and Environmental Engineering*. 2014, University of Chalmers of Technology: Gothenburg, Sweden.

43. Halliwell S. FRPs - The environmental agenda. *Advances in Structural Engineering*, 2010; 13(5): p. 783-791.

44. Ozbay K, Jawad D, Parker N A, Hussain S. Life-cycle cost analysis: State of the practice versus state of the art, in *Transportation Research Record*. 2004. p. 62-70.

45. Sandén B A. Standing the Test of Time: Signals and Noise From Environmental Assessments of Energy Technologies. *MRS Online Proceedings Library*, 2007; 1041.

46. Mara V, Al-Emrani M, Kliger R. Upgrading of an existing concrete-steel bridge using fibre reinforced polymer deck- A feasibility study. In: *Proceedings from the 1st FRP Bridges Conference* London, UK, 2012.

47. Handbook-MIL-HDBK M. 17-3F: Composite Materials Handbook, Volume 3-Polymer Matrix Composites Materials Usage, Design, and Analysis. 2002, US Department of Defense.

48. Heyliger P R, Reddy J N. Reduction of Free-Edge Stress Concentration. *Journal of Applied Mechanics*, 1985; 52(4): p. 801-805.

49. Hart-Smith L J. Mechanically-Fastened Joints for Advanced Composites — Phenomenological Considerations and Simple Analyses, in *Fibrous Composites in Structural Design*. 1980, Springer US. p. pp 543-574.

50. Tierney J J, Gillespie Jr J W, Bourban P E. 2.31 - Joining of Composites, in *Comprehensive Composite Materials*, A. Kelly and C. Zweben, Editors. 2000, Pergamon: Oxford. p. 1029-1047.

51. Thoppul S D, Finegan J, Gibson R F. Mechanics of mechanically fastened joints in polymer–matrix composite structures – A review. *Composites Science and Technology*, 2009; 69(3–4): p. 301-329.

52. Karakuzu R, Çalışkan C R, Aktaş M, İçten B M. Failure behavior of laminated composite plates with two serial pin-loaded holes. *Composite Structures*, 2008; 82(2): p. 225-234.

53. Camanho P P, Bowron S, Matthews F L. Failure mechanisms in bolted CFRP. *Journal of Reinforced Plastics and Composites*, 1998; 17(3): p. 205-233.

54. Ekh J, Schön J, Zenkert D. Simple and efficient prediction of bearing failure in single shear, composite lap joints. *Composite Structures*, 2013; 105(0): p. 35-44.

55. Rispler A R, Steven G P, Tong L. Photoelastic evaluation of metallic inserts of optimised shape. *Composites Science and Technology*, 2000; 60(1): p. 95-106.

56. McCarthy M A, Lawlor V P, Stanley W F, McCarthy C T. Bolt-hole clearance effects and strength criteria in single-bolt, single-lap, composite bolted joints. *Composites Science and Technology*, 2002; 62(10–11): p. 1415-1431.

57. Mottram J T, Zafari B. Pin-bearing strengths for bolted connections in fibre-reinforced polymer structures. *Proceedings of the ICE - Structures and Buildings*, 2011; 164: p. 291-305.

58. Collings T A. The strength of bolted joints in multi-directional cfrp laminates. *Composites*, 1977; 8(1): p. 43-55.

59. Rosner C N. Single-bolted connections for orthotropic fibre-reinforced composite structural members, in *Department of Civil Engineering*. 1992, University of Manitoba: Winnipeg, Manitoba.

60. Catalanotti G, Camanho P P, Ghys P, Marques A T. Experimental and numerical study of fastener pull-through failure in GFRP laminates. *Composite Structures*, 2011; 94(1): p. 239-245.

61. Oppe M, Feldmann M, Sedlacek G. Load bearing behaviour of mechanically fastened connections in glass-fibre reinforced polymers. In: *Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)*, Zurich, Switzerland, 2008.

62. Turvey G J. Experimental evaluation of bolt pull-through in pultruded glass-fibre-reinforced polymer plate. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 2011; 164(5): p. 307-319.

63. Banbury A, Kelly D W. A study of fastener pull-through failure of composite laminates. Part 1: Experimental. *Composite Structures*, 1999; 45(4): p. 241-254.

64. Gray P J, O'Higgins R M, McCarthy C T. Effect of thickness and laminate taper on the stiffness, strength and secondary bending of single-lap, single-bolt countersunk composite joints. *Composite Structures*, 2014; 107(0): p. 315-324.

65. Mosallam A S. Design Guide for FRP Composite Connections. Reston, Virginia: American Society of Civil Engineers (ASCE), 2011.

66. Wang H S, Hung C L, Chang F K. Bearing failure of bolted composite joints. Part I: Experimental characterization. *Journal of Composite Materials*, 1996; 30(12): p. 1284-1313.

67. Ireman T, Ranvik T, Eriksson I. On damage development in mechanically fastened composite laminates. *Composite Structures*, 2000; 49(2): p. 151-171.

68. Xiao Y, Ishikawa T. Bearing strength and failure behavior of bolted composite joints (part I: Experimental investigation). *Composites Science and Technology*, 2005; 65(7–8): p. 1022-1031.

69. Wu P S, Sun C T. Modeling bearing failure initiation in pin-contact of composite laminates. *Mechanics of Materials*, 1998; 29(3–4): p. 325-335.

70. Öndürücü A, Esendemir Ü, Tunay R F. Progressive failure analysis of glass–epoxy laminated composite pinned-joints. *Materials & Design*, 2012; 36(0): p. 617-625.

71. Khashaba U A, Sebaey T A, Alnefaie K A. Failure and reliability analysis of pinned-joints composite laminates: Effects of stacking sequences. *Composites Part B: Engineering*, 2013; 45(1): p. 1694-1703.

72. Wang Z, Zhou S, Zhang J, Wu X*, et al.* Progressive failure analysis of bolted single-lap composite joint based on extended finite element method. *Materials & Design*, 2012; 37(0): p. 582-588.

73. Abd-El-Naby S F M, Hollaway L. The experimental behaviour of bolted joints in pultruded glass/polyester material. Part 1: Single-bolt joints. *Composites*, 1993; 24(7): p. 531-538.

74. Hart-Smith L J. Design and Analysis of Bolted and Riveted Joints in Fibrous Composite Structures, in *Recent Advances in Structural Joints and Repairs for Composite Materials*, L. Tong and C. Soutis, Editors. 2003, Springer Netherlands. p. 211-254.

75. Ascione F, Feo L, Maceri F. An experimental investigation on the bearing failure load of glass fibre/epoxy laminates. *Composites Part B: Engineering*, 2009; 40(3): p. 197-205.

76. Zafari B, Mottram J T. Effect of orientation on pin-bearing strength for bolted connections in pultruded joints. In: *6th*

International Conference on FRP Composites in Civil Engineering Rome, Italy, 2012.

77. Yuan R L, Liu C J. Experimental characterization of FRP mechanical connections. In: *3rd International Conference on Advanced Composite Materials in Bridges and Structures ACMBS-3*, Montreal, Canada, 2000. The Canadian Society for Civil Engineers.

78. Collings T A, Beauchamp M J. Bearing deflection behaviour of a loaded hole in CFRP. *Composites*, 1984; 15(1): p. 33-38.

79. Turvey G J. Single-bolt tension joint tests on pultruded GRP plate — effects of tension direction relative to pultrusion direction. *Composite Structures*, 1998; 42(4): p. 341-351.

80. Kretsis G, Matthews F L. The strength of bolted joints in glass fibre/epoxy laminates. *Composites*, 1985; 16(2): p. 92-102.

81. Matthews F L, Roshan A A, Phillips L N. The bolt bearing strength of glass/carbon hybrid composites. *Composites*, 1982; 13(3): p. 225-227.

82. Park H-J. Effects of stacking sequence and clamping force on the bearing strengths of mechanically fastened joints in composite laminates. *Composite Structures*, 2001; 53(2): p. 213-221.

83. Smith P A, Pascoe K J. The effect of stacking sequence on the bearing strengths of quasi-isotropic composite laminates. *Composite Structures*, 1986; 6(1-3): p. 1-20.

84. Marshall I H, Arnold W S, Wood J, Mousley R F. Observations on bolted connections in composite structures. *Composite Structures*, 1989; 13(2): p. 133-151.

85. Aktas A, Dirikolu M H. The effect of stacking sequence of carbon epoxy composite laminates on pinned-joint strength. *Composite Structures*, 2003; 62(1): p. 107-111.

86. Quinn W J, Matthews F L. Effect of stacking sequence on the pin-bearing strength in glass fibre reinforced plastic. *Journal of Composite Materials*, 1977; 11: p. 139-145.

87. Camanho P P, Fink A, Obst A, Pimenta S. Hybrid titanium–CFRP laminates for high-performance bolted joints. *Composites Part A: Applied Science and Manufacturing*, 2009; 40(12): p. 1826-1837.

88. Kolks G, Tserpes K I. Efficient progressive damage modeling of hybrid composite/titanium bolted joints. *Composites Part A: Applied Science and Manufacturing*, 2014; 56(0): p. 51-63.

89. Fink A, Camanho P P, Andrés J M, Pfeiffer E, *et al.* Hybrid CFRP/titanium bolted joints: Performance assessment and application to a spacecraft payload adaptor. *Composites Science and Technology*, 2010; 70(2): p. 305-317.

90. Qin T, Zhao L, Zhang J. Fastener effects on mechanical behaviors of double-lap composite joints. *Composite Structures*, 2013; 100(0): p. 413-423.

91. Starikov R, Schön J. Fatigue resistance of composite joints with countersunk composite and metal fasteners. *International Journal of Fatigue*, 2002; 24(1): p. 39-47.

92. Erki M A. Bolted glass-fibre-reinforced plastic joints. *Canadian journal of civil engineering*, 1995; 22(4): p. 736-744.

93. Matharu N S, Mottram J T. Laterally unrestrained bolt bearing strength: Plain pin and threaded values in *6th International Conference on FRP Composites Composites in Civil Engineering Engineering*. 2012: Rome, Italy.

94. Sen F, Pakdil M, Sayman O, Benli S. Experimental failure analysis of mechanically fastened joints with clearance in composite laminates under preload. *Materials & Design*, 2008; 29(6): p. 1159-1169.

95. Kapti S, Sayman O, Ozen M, Benli S. Experimental and numerical failure analysis of carbon/epoxy laminated composite joints under different conditions. *Materials & Design*, 2010; 31(10): p. 4933-4942.

96. Turvey G, Gode J. An experimental investigation of the tensile behaviour of single-lap bolted joints in pultruded GFRP plate. In: *1st FRP Bridges Conference* London, UK, 2012.

97. Cooper C, Turvey G J. Effects of joint geometry and bolt torque on the structural performance of single bolt tension joints in pultruded GRP sheet material. *Composite Structures*, 1995; 32(1–4): p. 217-226.

98. Choi J H, Ban C S, Kweon J H. Failure load prediction of a mechanically fastened composite joint subjected to a clamping force. *Journal of Composite Materials*, 2008; 42(14): p. 1415-1429.

99. Stockdale J H, Matthews F L. The effect of clamping pressure on bolt bearing loads in glass fibre-reinforced plastics. *Composites*, 1976; 7(1): p. 34-38.

100. Tong L. Bearing failure of composite bolted joints with non-uniform bolt-to-washer clearance. *Composites Part A: Applied Science and Manufacturing*, 2000; 31(6): p. 609-615.

101. Dunthinh D. Connections of fibre-reinforced polymer (FRP) structural members: A review of the state of the art. 2000: Gaithersburg, Maryland.

102. Shivakumar K N, Crews J H. Bolt clamp-up relaxation in a graphite/epoxy laminate. 1982, NASA.

103. Horn W J, Schmitt R R. Relaxation in bolted thermoplastic composite joints. In: *Collection of Technical Papers - AIAA/ASME Structures, Structural Dynamics and Materials Conference*, 1993.

104. Turvey G J, Wang P. Failure of pultruded GRP bolted joints: a Taguchi analysis. Proceedings of the ICE - Engineering and Computational Mechanics, 2009. **162**, 155-166.

105. Lawlor V P, McCarthy M A, Stanley W F. An experimental study of bolt–hole clearance effects in double-lap, multi-bolt composite joints. *Composite Structures*, 2005; 71(2): p. 176-190.

106. McCarthy M A, McCarthy C T, Padhi G S. A simple method for determining the effects of bolt–hole clearance on load distribution in single-column multi-bolt composite joints. *Composite Structures*, 2006; 73(1): p. 78-87.

107. Kiral B G. Effect of the clearance and interference-fit on failure of the pin-loaded composites. *Materials & Design*, 2010; 31(1): p. 85-93.

108. Kelly G, Hallström S. Bearing strength of carbon fibre/epoxy laminates: effects of bolt-hole clearance. *Composites Part B: Engineering*, 2004; 35(4): p. 331-343.

109. Pierron F, Cerisier F, Grediac M. Numerical and experimental study of woven composite pin-joints. *Journal of Composite Materials*, 2000; 34(12): p. 1028-1054.

110. Yuan R L, Liu C J, Daley T. Study of mechanical connection for GFRP laminated structures. In: *2nd International Conference on Advanced Composite Materials in Bridges and Structures ACMBS-2*, Whistler, Canada, 1996. The Canadian Society for Civil Engineers.

111. Zafari B, Mottram J T. Pin-Bearing Strengths for Design of Bolted Connections in Pultruded Structures, in *CICE 2010 - The 5th International Conference on FRP Composites in Civil Engineering*. 2010: Beijing, China.

112. Kim S-Y, Hennigan D J, Kim D. Influence of Fabrication and Interference-Fit Techniques on Tensile and Fatigue Properties of Pin-Loaded Glass Fiber Reinforced Plastics Composites. *Journal of Engineering Materials and Technology*, 2012; 134(4): p. 041012-041012.

113. Wei J, Jiao G, Jia P, Huang T. The effect of interference fit size on the fatigue life of bolted joints in composite laminates. *Composites Part B: Engineering*, 2013; 53(0): p. 62-68.

114. Zhao Q, Lei Y, Huadong L, Fenglei L*, et al.* The Interference-Fit Bolted Joining of Hybrid Metal/Composite. *SAE International Journal of Materials and Manufacturing*, 2013; 6(1).

115. Pradhan B, Babu P R. Assessment of beneficial effects of interference-fit in pin-loaded FRP composites. *Journal of reinforced plastics and composites*, 2007; 26(8): p. 771-788.

116. Cole R T, Bateh E J, Potter J. Fasteners for composite structures. *Composites*, 1982; 13(3): p. 233-240.

117. Kim S-Y, He B, Shim C-S, Kim D. An experimental and numerical study on the interference-fit pin installation process for cross-ply glass fiber reinforced plastics (GFRP). *Composites Part B: Engineering*, 2013; 54(0): p. 153-162.

118. Schön J. Coefficient of friction of composite delamination surfaces. *Wear*, 2000; 237(1): p. 77-89.

119. Schön J. Coefficient of friction and wear of a carbon fiber epoxy matrix composite. *Wear*, 2004; 257(3–4): p. 395-407.

120. Mottram J T. Friction and load transfer in bolted joints of pultruded fibre reinforced polymer section, in *FRP Composites in Civil Engineering - CICE 2004*. 2004, Taylor & Francis. p. 845-850.

121. Olmedo Á, Santiuste C. On the prediction of bolted single-lap composite joints. *Composite Structures*, 2012; 94(6): p. 2110-2117.

122. Karakuzu R, Gülem T, İçten B M. Failure analysis of woven laminated glass–vinylester composites with pin-loaded hole. *Composite Structures*, 2006; 72(1): p. 27-32.

123. Wang Y. Bearing behavior of joints in pultruded composites. *Journal of Composite Materials*, 2002; 36(18): p. 2199-2216.

124. Waddoups M E, Eisenmann J R, Kaminski B E. Macroscopic fracture mechanics of advanced composite materials. *Journal of Composite Materials*, 1971; 5: p. 446-454.

125. Ascione F, Feo L, Maceri F. On the pin-bearing failure load of GFRP bolted laminates: An experimental analysis on the influence of bolt diameter. *Composites Part B: Engineering*, 2010; 41(6): p. 482-490.

126. Gray P J, O'Higgins R M, McCarthy C T. Effects of laminate thickness, tapering and missing fasteners on the mechanical behaviour of single-lap, multi-bolt, countersunk composite joints. *Composite Structures*, 2014; 107(0): p. 219-230.

127. Gray Jr E F, Browne H C, Burkhardt W, Fowler T J*, et al.* Structural plastics design manual. *Manuals and Reports on Engineering Practice, American Society of Civil Engineers*, 1984(63).

128. Ekh J, Schön J. Effect of secondary bending on strength prediction of composite, single shear lap joints. *Composites Science and Technology*, 2005; 65(6): p. 953-965.

129. Hoa S V, Di Maria A, Feldman D. Inserts for fastening sheet molding compounds. *Composite Structures*, 1987; 8(4): p. 293-309.

130. Nilsson S. Increasing strength of graphite/epoxy bolted joints by introducing an adhesively bonded metallic insert. *Journal of composite materials*, 1989; 23(7): p. 642-650.

131. Herrera-Franco P J, Cloud G L. Strain-relief inserts for composite fasteners. An experimental study. *Journal of Composite Materials*, 1992; 26(5): p. 751-768.

132. Rufin A C. Fastener hole reinforcement in composites using cold-expanded inserts. *Journal of Composites Technology and Research*, 1995; 17(2): p. 145-151.

133. Mirabella L, Galea S C. An experimental investigation into the use of inserts to enhance the static performance of thin composite bolted lap joints. In: *Eleventh International Conference on Composite Materials*, Queensland, Australia, 1997. Australian Composite Structures Society Woodhead Publishing Limited.

134. Camanho P P, Matthews F L. Bonded metallic inserts for bolted joints in composite laminates. *Proceedings of the Institution of Mechanical Engineers Part L: Journal of Materials: Design and Applications*, 2000; 214(1): p. 33-40.

135. Camanho P P, Tavares C M L, de Oliveira R, Marques A T, *et al.* Increasing the efficiency of composite single-shear lap joints using bonded inserts. *Composites Part B: Engineering*, 2005; 36(5): p. 372-383.

136. Kradinov V, Madenci E, Ambur D R. Bolted lap joints of laminates with varying thickness and metallic inserts. *Composite Structures*, 2005; 68(1): p. 75-85.

137. Mazraehshahi H T, Zakeri A. Influence of material and geometrical parameters on stress field of composite plates with insert. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2012; 226(12): p. 1573-1582.

138. Turvey G J, Wang P. 5.3 A critique of the EUROCOMP simplified design method for bolted joints in long fibre reinforced polymer composite materials, in *Advanced Polymer Composites for Structural Applications in Construction*. 2002. p. pp 301-308.

139. Turvey G J, Wang P. An FE analysis of the stresses in pultruded GRP single-bolt tension joints and their implications for joint design. *Computers & Structures*, 2008; 86(9): p. 1014-1021.

140. Oppe M, Knippers J. Behaviour of bolted connections in GFRP subjected to tension loads. In: *4th International Conference on Advanced Composites in Construction 2009, ACIC 2009*, 2009.

141. Rosner C N, Rizkalla S H. Bolted connections for fiber-reinforced composite structural members: Analytical model and design recommendations. *Journal of Materials in Civil Engineering*, 1995; 7(4): p. 232-238.

142. ASCE: Pre-standard for load & resistance factor design (LRFD) of pultruded fiber reinforced polymer (FRP) structures, 2010. American Society of Civil Engineers.

143. Turvey G J. 3 - Bolted joints in pultruded glass fibre reinforced polymer (GFRP) composites, in *Composite Joints and Connections*, P. Camanho and L. Tong, Editors. 2011, Woodhead Publishing. p. 77-111.

144. Girão Coelho A M, Mottram J T. A review of the behaviour and analysis of bolted connections and joints in pultruded fibre reinforced polymers. *Materials & Design*, 2015; 74(0): p. 86-107.

145. Mays G C, Hutchinson. A R. Adhesives in Civil Engineering. Cambridge University Press, 1992.

146. Vallée T, Keller T. Adhesively bonded lap joints from pultruded GFRP profiles. Part III: Effects of chamfers. *Composites Part B: Engineering*, 2006; 37(4-5): p. 328-336.

147. Haghani R, Al-Emrani M, Kliger R. Stress distribution in adhesive joints with tapered laminates g - Effect of tapering length and material properties. *Journal of Composite Materials*, 2010; 44(3): p. 287-302.

148. Keller T, Vallée T. Adhesively bonded lap joints from pultruded GFRP profiles. Part II: joint strength prediction. *Composites Part B: Engineering*, 2005; 36(4): p. 341-350.

149. Haghani R, Al-Emrani M, Kliger R. Interfacial stress analysis of geometrically modified adhesive joints in steel beams strengthened with FRP laminates. *Construction and Building Materials*, 2009; 23(3): p. 1413-1422.

150. Keller T, Vallée T. Adhesively bonded lap joints from pultruded GFRP profiles. Part I: stress-strain analysis and failure modes. *Composites Part B: Engineering*, 2005; 36(4): p. 331-340.

151. Hart-Smith L J. Bonded-bolted composite joints. *Journal of Aircraft*, 1985; 22(11): p. 993-1000.

152. Chan W S, Vedhagiri S. Analysis of composite bonded/bolted joints used in repairing. *Journal of composite materials*, 2001; 35(12): p. 1045-1061.

153. Manalo A, Mutsuyoshi H. Behavior of fiber-reinforced composite beams with mechanical joints. *Journal of composite materials*, 2012; 46(4): p. 483-496.

154. Sawa T, Ishikawa H, Muto K. Strength of joints combining adhesives with bolts. (Cases where adherends are pipe flanges and circular flanges). *JSME International Journal, Series 1: Solid Mechanics, Strength of Materials*, 1992; 35(1): p. 38-44.

155. Fu M, Mallick P K. Fatigue of hybrid (adhesive/bolted) joints in SRIM composites. *International Journal of Adhesion and Adhesives*, 2001; 21(2): p. 145-159.

156. Lin W-H, Lin C-H, Jen M-H R. An innovative fatigue method in single-lapped mixed composite joints. *Journal of reinforced plastics and composites*, 2004; 23(9): p. 997-1017.

157. Vinson J R. Mechanical fastening of polymer composites. *Polymer Engineering & Science*, 1989; 29(19): p. 1332-1339.

158. Kelly G. Quasi-static strength and fatigue life of hybrid (bonded/bolted) composite single-lap joints. *Composite Structures*, 2006; 72(1): p. 119-129.

159. Kelly G. Load transfer in hybrid (bonded/bolted) composite single-lap joints. *Composite Structures*, 2005; 69(1): p. 35-43.

160. Hoang-Ngoc C-T, Paroissien E. Simulation of single-lap bonded and hybrid (bolted/bonded) joints with flexible adhesive. *International Journal of Adhesion and Adhesives*, 2010; 30(3): p. 117-129.

161. Bodjona K, Lessard L. Load sharing in single-lap bonded/bolted composite joints. Part II: Global sensitivity analysis. *Composite Structures*, 2015; 129(0): p. 276-283.

162. Vallée T, Tannert T, Meena R, Hehl S. Dimensioning method for bolted, adhesively bonded, and hybrid joints involving Fibre-Reinforced-Polymers. *Composites Part B: Engineering*, 2013; 46(0): p. 179-187.

163. Mottram J, Turvey G J. Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems. *Progress in Structural Engineering and Materials*, 2003; 5(4): p. 195-222.

164. Qian H, Sun C T. Performance of a composite double strap joint with attachments. In: *Joining and Repair of Composites Structures*, Kansas City, MO; United States, 2004. ASTM Special Technical Publication.

165. Turaga U V R S, Sun C T. Improved design for metallic and composite single-lap joints. *Journal of Aircraft*, 2008; 45(2): p. 440-447.

166. Kumar B, Sun C T, Wang P H, Sterkenburg R. Adding additional load paths in a bonded/bolted hybrid joint. *Journal of Aircraft*, 2010; 47(5): p. 1593-1598.

167. Sun C T, Kumar B, Wang P, Sterkenburg R. Strength enhancement of hybrid (bonded/bolted) joints for composites using attachments. In: *1st Joint Canadian-American Technical Conference on Composites*, Newark, DE; United States, 2009.

168. Evernden M C, Toby Mottram J. A case for houses to be constructed of fibre reinforced polymer components. *Proceedings of Institution of Civil Engineers: Construction Materials*, 2012; 165(1): p. 3-13.

169. Hartley J, Hutchinson J. STARLINK lightweight building systems - Wholy polymeric structures. *FRP International*, 2013; 10(2): p. 3-6.

170. Mara V, Al-Emrani M, Haghani R. A novel connection for fibre reinforced polymer bridge decks: Conceptual design and experimental investigation. *Composite Structures*, 2014; 117(0): p. 83-97.

171. Weitzenböck J R, McGeorge D. Science and technology of bolt-adhesive joints, in *Advanced Structured Materials*. 2011. p. 177-199.

172. Stocchi C, Robinson P, Pinho S T. A detailed finite element investigation of composite bolted joints with countersunk fasteners. *Composites Part A: Applied Science and Manufacturing*, 2013; 52(0): p. 143-150.

173. ASTM: Standard D3039/D3039M−14: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*,* 2014. ASTM International, United States.

174. Baley C, Perrot Y, Davies P, Bourmaud A*, et al.* Mechanical properties of composites based on low styrene emission polyester resins for marine applications. *Applied Composite Materials*, 2006; 13(1): p. 1-22.

175. Highsmith A L, Reifsnider K L. Stiffness-reduction mechanisms in composite laminates. *Damage in composite materials, ASTM STP*, 1982; 775: p. 103-117.

176. Reifsnider K L, Masters J E. Investigation of characteristic damage states in composite laminates. *American Society of Mechanical Engineers (Paper)*, 1978(78 WA/Aero-4).

177. Hahn H T, Tsai S W. On the behavior of composite laminates after initial failures. *Journal of Composite Materials*, 1974; 8: p. 288-305.

178. Talreja R. Transverse cracking and stiffness reduction in composite laminates. *Journal of Composite Materials*, 1985; 19(4): p. 355-375.

179. Garrett K W, Bailey J E. Multiple transverse fracture in 90° cross-ply laminates of a glass fibre-reinforced polyester. *Journal of Materials Science*, 1977; 12(1): p. 157-168.

180. Reifsnider K L, Highsmith A. The relationship of stiffness changes in composite laminates to fracture-related damage mechanisms. In: *Fracture of Composite Materials, Proceedings of the 2nd USA-USSR Symposium*, Bethlehem, Pa, USA, 1982.

181. ASTM: Standard D3410/D3039M−03: Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading, 2014. ASTM International, United States.

182. ASTM: Standard D7078/D7078M−12: Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail shear method, 2014. ASTM International, United States.

183. ASTM: Standard D5961/D5961M−13: Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates, 2013. ASTM International, United States.

184. Liu D, Tang Y, Cong W L. A review of mechanical drilling for composite laminates. *Composite Structures*, 2012; 94(4): p. 1265-1279.

185. Mottram T. Determination of pin-bearing strength for the design of bolted connections with standard pultruded profiles. In: *Advanced Composites in Construction 2009, ACIC 2009 - Proceedings of the 4th International Conference*, 2009.

186. Román J d C S. Experiments on Epoxy, Polyurethane and ADP Adhesives. 2005, Composite Contruction Laboratory: Switzerland.

187. Lopez-Anido R. Open-hole tensile strength for pultruded plates. Report to ASCE Fiber Composites and Plastics Committee. 2009: University of Maine.

188. Cunningham D, Harries K A, Bell A J. Open-hole tension capacity of pultruded GFRP having staggered hole arrangement. *Engineering Structures*, 2015; 95(0): p. 8-15.