THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Durability and Long-term Performance of Adhesively Bonded FRP/steel Joints

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Cover:

Schematics of different damaging mechanisms of hygrothermal ageing conditions in adhesively bonded FRP/steel joints, and some examples of the experimental and numerical investigations performed in this project.

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To Parisa

For your love, your patience, and your faith.

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ABSTRACT

Fibre reinforced polymer (FRP) composites offer excellent properties, such as high specific strength and stiffness, corrosion resistance and light weight. Over the past four decades, FRPs have been increasingly used for strengthening and repair of bridge structures, and more recently, in the manufacture of whole/hybrid FRP bridges. Although, the short-term behaviour of FRP/steel bonded joints has been extensively studied, the subject of the long-term performance and durability has not been researched to the same degree. Today, uncertainties regarding the durability aspects of adhesively bonded FRP/steel joints present a major obstacle to their growing application. This thesis aims to deepen the understanding of the structural effects of environmental exposure conditions relevant to bridges on bonded FRP/steel joints, with a focus on predicting the mechanical response of aged joints.

Firstly, to map out the research needs, a comprehensive state-of-the-art literature review was carried out, and the most important identified knowledge-gaps were pursued for research. An extensive experimental programme was conducted including long-term testing of bonded FRP/steel joints that were subjected to various temperature ranges, humidity levels, and cyclic exposure scenarios. Among other factors, the effects of adhesive layer thickness and type of FRP material were investigated. The results showed the importance of FRP permeability on moisture and damage distribution profile in bonded joints. In addition, freeze–thaw cycles were found to have no unfavourable effects on the strength of dry or preconditioned joints. Complementary material characterization tests were also conducted to study moisture diffusion kinetics. These results underlined the importance of considering the exposure history for prediction and design purposes. Furthermore, the dependency of cohesive laws of the adhesive material on environmental exposure was investigated using an innovative approach based on open-face specimens in conjunction with the J-integral analysis.

FE simulations were incorporated to predict the mechanical response of joints after environmental ageing. Firstly, the applicability of the cohesive zone modelling approach to strength prediction of bonded FRP/steel joints was investigated. The results confirmed the accuracy of the predictions provided that the variation of failure modes were taken into account. Moreover, the minimum required overlap length was found to be directly proportional to the shape of cohesive laws. This finding, in combination with the environmental-dependent cohesive laws, can be employed in the design phase to ensure sufficient anchorage length after in-service exposure. Lastly, sequentially coupled moisture diffusion–fracture analysis were found to provide reasonable predictions of the mechanical behaviour of environmentally aged joints. This study provides the basis for durability-related experimental characterisation methods and predictive modelling of adhesively bonded FRP/steel joints.

Keywords: fibre reinforced polymer, durability, long-term performance, adhesively bonded joints, FRP/steel joints, moisture diffusion, cohesive zone modelling

PREFACE

The work presented in this thesis explores the durability and long-term performance of adhesively bonded FRP/steel joints used in bridge applications. The project was carried out at the Department of Civil and Environmental Engineering, Division of Structural Engineering, Steel and Timber Structures, Chalmers University of Technology from May 2012 until February 2017. The author wishes to express his gratitude to the Swedish Research Institute, FORMAS, for financing this project.

I would like to express my sincere gratitude to my supervisors, Assoc. Prof. Mohammad Al-Emrani and Assoc. Prof. Reza Haghani, for their tremendous support, encouragement, and excellent guidance throughout this project. I could have not asked for better supervisors, and more importantly life-time friends. Assoc. Prof Al-Emrani was also my examiner during the second half of this project. Mohammad, you are an outstanding teacher, a brilliant researcher and a compassionate leader. It has been my privilege to work closely with you. Reza, I have enjoyed the opportunity to watch and learn from your vast knowledge and extensive experience. You made me believe in myself every time that I was stuck on research or had a tough time. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. I would also like to thank my former examiner Prof. Robert Kliger for all his good advice and continuous support.

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Gothenburg, 2017
Mohsen Heshmati

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers:

Paper I

Heshmati, M., Haghani, R., & Al-Emrani, M. (2015). Environmental durability of adhesively bonded FRP/steel joints in civil engineering applications: State of the art. *Composites Part B: Engineering*, *81*, 259–275. https://doi.org/10.1016/j.compositesb.2015.07.014

Paper II

Heshmati, M., Haghani, R., & Al-Emrani, M. (2016). Effects of Moisture on the Long-term Performance of Adhesively Bonded FRP/steel Joints Used in Bridges. *Composites Part B: Engineering*, *92*, 1–16. https://doi.org/10.1016/j.compositesb.2016.02.02

Paper III

Heshmati, M., Haghani, R., Al-Emrani, M., & André, A. (2016). On the design of adhesively bonded FRP-steel joints using cohesive zone modelling. Submitted to *Theoretical and Applied Fracture Mechanics.*

Paper IV

Heshmati, M., Haghani, R., & Al-Emrani, M. (2017). Durability of bonded FRP-to-steel joints: effects of moisture, de-icing salt solution, temperature and FRP type. Accepted for publication in *Composites Part B: Engineering.*

Paper V

Heshmati, M., Haghani, R., & Al-Emrani, M. (2017). Dependency of cohesive laws of a structural adhesive in Mode-I and Mode-II loading on moisture, freeze/thaw cycling, and their synergy. Accepted for publication in *Materials and Design*.

Paper VI

Heshmati, M., Haghani, R., & Al-Emrani, M. (2017). Durability of CFRP/steel joints under cyclic wet-dry and freeze-thaw conditions. Submitted to *Composites Part B: Engineering*.

AUTHOR'S CONTRIBUTIONS TO JOINTLY PUBLISHED PAPERS

The contribution of the author of this thesis to the appended papers is described below:

Paper I: Responsible for conducting the literature review, planning and writing the paper. The co-authors reviewed the work and provided comments.

Paper II: Responsible for planning and writing the paper, numerical analyses and simulations. The co-authors contributed in planning and conducting the experiments, as well as reviewing the paper.

Paper III: Responsible for planning and writing the paper. Conducted the tests and FE simulations of DLS joints. The co-authors performed the DSR and beam tests, as well as FE simulations of beam specimens. The co-authors reviewed the work and provided comments.

Paper IV: Responsible for planning and writing the paper, analysing the experimental results and performing numerical analyses. The co-authors contributed in planning the experiments, manufacturing the specimens as well as reviewing the paper.

Paper V: Responsible for planning and writing the paper, numerical analyses, development of the test setups and conducting the experiments. The co-authors helped to manufacture the test specimens, reviewed the work and provided comments.

Paper VI: Responsible for planning and writing the paper, numerical analyses and conducting the experiments. The co-authors contributed in planning the experiments, manufacturing the specimens and reviewing the paper.

Other publications by the author

Journal papers

- Aygül, M., Bokesjö, M., Heshmati, M., & Al-Emrani, M. (2013): A comparative study of different fatigue failure assessments of welded bridge details. *International Journal of Fatigue*, 2013, 49, 62-72.
- Haghani, R., Al-Emrani, M., & Heshmati, M. (2012): Fatigue-prone details in steel bridges. *Buildings*, 2014, 2(4), 456-476.

Conference proceedings

- Heshmati, M., Haghani R., Al-Emrani, M. (2016): Experimental evaluation of the durability of adhesively bonded CFRP/steel joints in bridges. *Proc. Of 19th IABSE Congress on Challenges in Design and Construction of an Innovative and Sustainable Built Environment*, Stockholm, Sweden, 21-23 September 2016.
- Heshmati, M., Haghani, R., Al-Emrani, M. (2015). Hygrothermal Durability of Adhesively Bonded FRP/steel Joints. In S. Saha, Y. Zhang, S. Yazdani, & A. Singh (Eds.), Implementing Innovative Ideas in Structural Engineering and Project Management (pp. 75–80). Sydney: ISEC Press.
- Heshmati M., Haghani R. André A. and Al-Emrani M. (2014): Design of FRP/steel joints bonded with thick adhesive layers. *Proc. of the Second Intl. Conf. on Advances in Civil and Structural Engineering - CSE 2014*, Kuala Lumpur, Malaysia, 20-21 December 2014.
- Heshmati, M., Al-Emrani, M. (2012): Fatigue design of plated structures using structural hot spot stress approach. *Proceedings of the Sixth International Conference on Bridge Maintenance, Safety and Management - IABMAS 2012*, Stresa, Lake Maggiore, 8-12 July 2012. p. 3146-3153. ISBN 978-041562124-3.
- Heshmati, M., Al-Emrani, M. and Edlund B. (2012): Fatigue assessment of weld terminations in welded cover-plate details; a comparison of local approaches. *Nordic Steel Construction Conference*, Oslo, Sept 5-7, 2012. p. 781-790. ISBN 978-82-91466-12-5.

Licentiate thesis

- Heshmati, M. (2015): Hygrothermal Durability of Adhesively Bonded FRP/steel Joints. Chalmers University of Technology, Gothenburg, Sweden, 2015:02, ISSN 1652-9146.

Master's thesis

- Heshmati, M. (2012): Fatigue life assessment of bridge details using finite element method. Master's thesis, Chalmers University of Technology, Gothenburg, Sweden, 2012:03, ISSN 1652-9146.

Contents

Part I
Extended Summary

1 Introduction

1.1 Background

The design life of many civil engineering structures is 80-120 years, yet of many bridges that were built in different parts of the world in the beginning of the last century, the majority are still in service. According to study conducted in 2004 [1], steel bridges account for a large stock of old European bridges that have reached or will soon reach the end of their service-life. As opposed to rebuilding these bridges, strengthening and retrofitting could be a more economical solution provided that conventional repair methods are replaced by more durable and cost-effective upgrading techniques [2].

Fibre reinforced polymer (FRP) composites were firstly introduced in aerospace industry during 1940s. Despite superior properties of FRPs in structural applications, high production costs initially prevented their acceptance in extremely cost-driven and conservative construction industry. Nevertheless, continuous growth in FRP industry lowered production costs, and FRP materials finally found their acceptance in construction sector during the late 1980s [3]. FRPs offer superior advantages over conventional construction materials, such as steel, the most notable of which are their rusting resistance, high strength-to-weight ratio and light weight. With the advances in polymer science, adhesive bonding has become a prominent joining technology that possesses several advantages over mechanical fastening techniques, such as lower weight, less fabrication costs and more uniform stress distribution. The unique properties of FRP composites combined with advantages of adhesive bonding, has made FRP bonding an attractive method for strengthening, repair and refurbishment of existing structures.

In the past four decades, carbon fibre-reinforced polymer (CFRP) laminates have been used in practice to strengthen and repair concrete structures [4]. In the past few years, there has been also a trend towards the use of FRP bonding technique to strengthen and repair of steel [5,6] and timber structures [7,8]. Moreover, FRP materials have found their way into whole- and partial-FRP structures, e.g. using glass fibre-reinforced polymer (GFRP) deck systems on steel girders for the construction of hybrid FRP bridges or the refurbishment of existing steel bridges. As a result, there is a great deal of interest in studying the behaviour of FRP/steel adhesive joints from the short- and long-term behaviour perspectives.

One problem with the application of FRP/steel joints in construction industry is uncertainties regarding the long-term performance of such joints. As for many other structures exposed to outdoor environments, the effectiveness and strength of adhesively-bonded FRP/steel joints in bridges is dependent on environmental durability of each and every constituent. In spite of the fact that the FRP materials used in existing bridges have exhibited acceptable outdoor performance with very seldom problems being reported in the literature, their relatively new application and lack of knowledge regarding their long-term performance and environmental degradation mechanisms have hindered their widespread application in steel structures. This lack of knowledge is currently compensated by applying a multiple of large safety factors to the strength of composite materials, which dramatically increases the material usage [5,9].

Concerns related to the environmental durability of adhesive joints have been pointed out in recent research publications, in which understanding the underlying mechanisms of degradation [10–12] and quantifying the long-term performance [13,14] have been in focus. However, most of these research projects have been conducted within fields such as aerospace and automobile industry that have distinct differences with civil engineering applications [15,16]. Loading types, curing conditions, operating environments, material production, joint geometry, and manufacturing conditions are some examples of the aforementioned dissimilarities. In fact, there is still a lack of knowledge about the long-term performance of different adhesives and FRP composites (i.e. on material level) used in infrastructural applications.

A common approach to investigate the long-term performance issues is to use accelerated testing scenarios. In such tests, usually very harsh scenarios are formulated to achieve high damage rate in a relatively short time. Nevertheless, due to the unrealistically severe applied conditions, these tests tend to exaggerate the degradation rate [17]. Furthermore, the use of accelerating parameters, such as high temperature, may activate damaging mechanisms that may never happen during the life of a bridge. Hence, while the use of such conditions may be justifiable for automotive and aerospace industries, their validity for bridges and similar structures, with a much longer service life and less harsh exposure conditions, is doubtful. Another shortcoming of accelerated tests is the lack of time correlation between the test and real service conditions, which makes it almost impossible to accurately predict the service life.

With the improved computational capabilities in recent years, numerical methods have provided new possibilities to investigate complex issues, such as the long-term performance, more effectively. However, the results obtained from these methods need to be correlated and verified by observations and/or testing of structures in real conditions before they can be considered reliable. In addition, given the uncertainties regarding the long-term behaviour of bonded FRP joints in bridge structures, modelling the possible synergies between various damaging mechanisms becomes inherently cumbersome. Therefore, there is a large need to develop accurate durability data and experimentally verified assessment approaches valid for adhesively bonded FRP/steel joints used in bridge applications.

1.2 Aim and objectives

The overall aim of the project is to establish a framework for the long-term performance and durability assessment of adhesively bonded FRP/steel joints exposed to any combination of moisture and temperature. Within this overall aim, the following main objectives are defined and covered in this thesis:

- To review the state-of-the-art on durability of FRP composites, structural adhesives and FRP/steel bonded joints used in bridge applications with the emphasis on identifying the influential environmental factors, damaging mechanisms, and collecting the available long-term performance data.
- To study the influence of various geometrical and material parameters, relevant to durability aspects, on mechanical behaviour of FRP/steel joints using advanced numerical methods such as the damage mechanics.
- To characterize the temperature, moisture and exposure-history dependent material properties and implement the outcome in the developed modelling procedure.
- To investigate how hygrothermal, wet-dry and freeze-thaw exposure conditions can affect the mechanical properties of adhesively bonded FRP/steel joints.
- To predict the residual strength and mechanical response of environmentally aged bonded joints exposed to hygrothermal and cyclic ageing conditions.

1.3 Methodology and scientific approach

Figure 1.1 shows the methodology that was used to realize the overall aim of this project. As can be seen, both experimental and numerical tools were used. An extensive literature study was performed to obtain the state-of-the-art on durability of adhesively bonded FRP/steel joints used in civil engineering applications. Special consideration was given to identifying the common long-term performance assessment approaches, possible synergies between various ageing factors, and the most relevant available experimental studies.

Based on the findings of the literature study, a series of experiments were designed to characterize the effect of various ageing conditions at material- and joint-level. Given that the aim of the project is to establish a methodology that can be applicable to any types of composites, adhesives, etc., no attempt is made to compare different types of materials. Hence, only one type of each material is used in the experimental work. Furthermore, the applicability of the cohesive zone modelling concept to predict the strength of bonded FRP/steel joints, with interfacial, cohesive or FRP delamination failure modes, was investigated by means of 2D and 3D finite element (FE) analyses. In addition, coupled 3D FE analyses were performed to study the effects of ageing in humid conditions on the mechanical response and fracture of bonded FRP/steel joints.

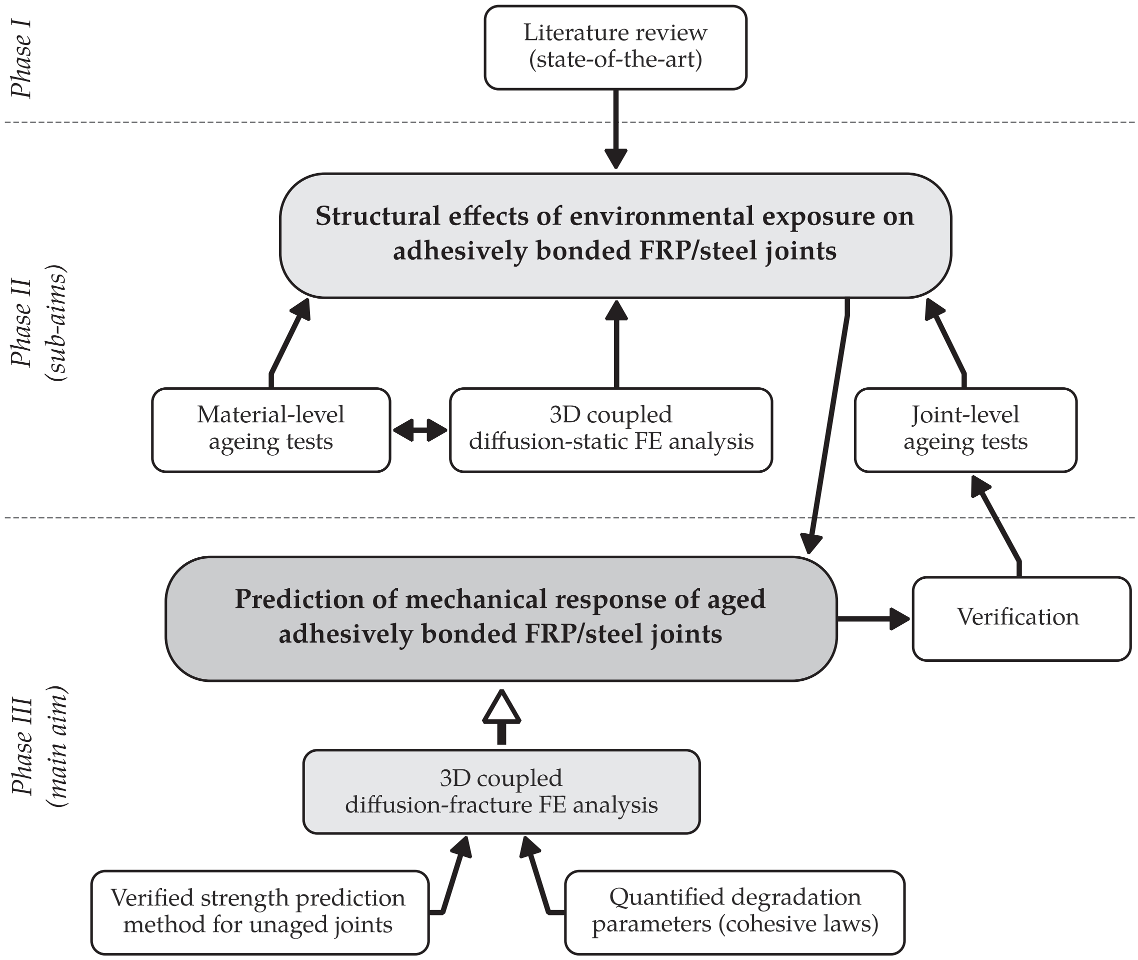

Figure 1.1. *Method for the study*

1.4 Limitations

The work in this thesis involved studying the durability of adhesively bonded FRP/steel joints. The following limitations apply:

(1) The exposure environments, materials and configurations were chosen to be representative of the application of bonded FRP/steel joints in a typical bridge in Sweden.

(2) Only one type of adhesive, steel, CFRP, and GFRP materials were considered, and therefore the results might not be applicable to other materials.

(3) Only temperatures below the glass transition temperature of adhesive were utilized.

(4) Only quasi-static loads were considered.

(5) The interfacial moisture diffusion, creep and load-assisted diffusion were neglected in the moisture diffusion finite element analyses.

(6) Only the effects of ageing at a structural-level were investigated.

1.5 Significance of research

The original contributions of this research are summarised as follows:

- A detailed review on environmental durability of adhesively bonded FRP/steel joints in civil engineering applications is provided (**Paper I**). Special attention is paid to the effects of moisture, temperature as well as their combined action at both material and joint-level. The review covers most of the new research results in this field. Scientific community (especially young researchers) could directly benefit from the paper, the list of references, and the identified knowledge-gaps.
- Experiments were conducted to study the structural effects of moisture on FRP materials used in bridges (**Paper II** and **Paper IV**). The results of these investigations contribute to the long-term data of FRPs used in construction sector, which are limited. Furthermore, the numerical results provide additional knowledge and understanding on the mechanical behaviour of FPR/steel adhesive joints in the presence of moisture.
- The structural effects of moisture, de-icing salt solution, temperature, FRP type, and adhesive layer thickness were investigated using a comprehensive experimental programme (**Paper IV**). Residual strength tests were performed after extended exposure durations (up to three years). These tests provide information on the combined and isolated effects of some of the investigated factors, which is to the authors' knowledge, rare if not unique.
- The strength and mechanical behaviour of a number of different configurations with various failure modes are successfully predicted using the directly measured cohesive laws (**Paper III**). This method does not require further calibration or back-calculation of the material data that is often used by other researchers.
- The effects of moisture, freeze-thaw cycles and their synergy on fracture properties (cohesive laws) of an adhesive was measured using a novel approach (**Paper V**). This method is based on open-face specimens in conjunction with the J-integral analysis, which allows for fast moisture diffusion into the adhesive layer and minimizes the dimensions of specimens. Such experiments have not been reported before and are useful from an engineering perspective.
- Bridges are frequently exposed to environmental conditions with cyclic nature. This subject was investigated using extensive experiments at material- and joint-level subjected to various cyclic environmental scenarios (**Paper VI**). In addition, multi-physics numerical modelling tools were used to develop a predictive modelling platform for residual strength prediction of these joints. To the authors' knowledge, the combined effects of moisture and thermal cycles, such as freeze/thaw, on the strength of bonded joints have been scarcely investigated.

1.6 Outline of the thesis

This thesis consists of an introductory section and six appended papers.

In Chapter 1, the background of the work, aim, objectives and scope of the study together with a general description of its scientific methods and original contributions are provided.

Chapter 2 present an overview of the predictive durability-modelling approaches that could be used to predict the strength of bonded composite joints after extended in-service exposure.

Chapter 3 introduces the environmental durability of adhesively bonded FRP/steel joints by reporting the effects of moisture and temperature on FRP composites, epoxy adhesives, and bonded joints. This knowledge is extended through **Paper I** which presents a review on environmental durability of adhesively bonded FRP/steel joints

Chapter 4 deals with fundamental aspects of cohesive zone modelling and relevant characterisation methods; for more details see **Paper III**, **V**.

Chapter 5 provides an overview of the experimental programme. Different tests and environmental conditions are described, see **Paper II**, **IV**, and **VI**.

Chapter 6 presents the most important results of the work in terms of a brief summary of appended papers.

In Chapter 7, the main conclusions from this work are drawn and suggestions for the future work are given.

2 Predictive durability-modelling approaches

2.1 Introduction

Adhesively bonded composite joints have been increasingly used in car and aviation industries. In these industries, the well-known merits of modern adhesives have made them the preferred joining method in many applications. The range of applications of adhesive joints in construction industry, however, is still limited largely due to uncertainties regarding their design and long-term performance. On the one hand, many civil structures are generally designed to be in-service for more than 80 years, which is several times more than the service life of cars or airplanes. On the other hand, the application of adhesives in construction projects is mainly *in-situ*, which is generally accompanied by lack of a controlled application environment and rather insufficient quality assurance procedures. Major differences in loading conditions and exposure environments also adds to the complexity associated with their design.

The abovementioned uncertainties are currently compensated by applying a multiple of large safety factors to the strength of composite and adhesive materials , which dramatically reduces the efficiency [5,9]. The tendency to "overdesign" the adhesively bonded composite joints has hindered their broader application in civil engineering projects. This issue can be circumvented by employing predictive methods that can reliably estimate the strength of bonded composite joints before and after extended in-service exposure. The literature on predictive methods that account for the effects of environmental exposure shows a variety of approaches, which can be categorized under four main models, see Figure 2.1.

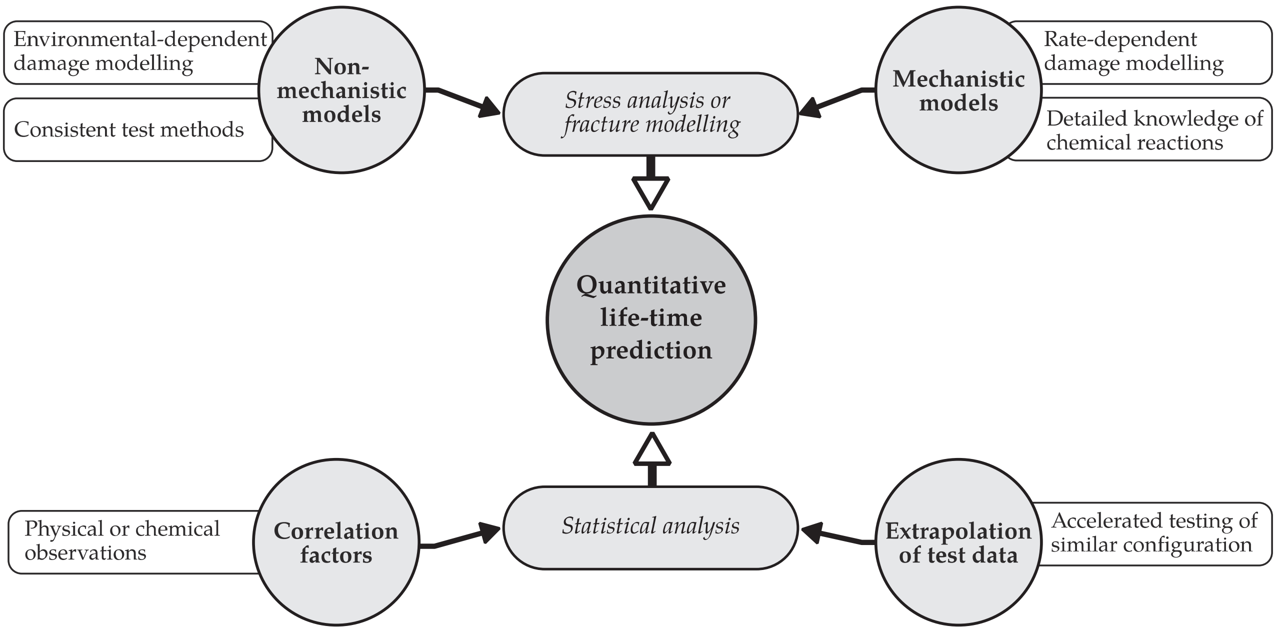

Figure 2.1 *Predictive durability-modelling approaches proposed in the literature*

2.2 Mechanistic models

The mechanistic models are based on relating the activated chemical reactions, upon exposure to environmental conditions, to the damage progression in bonded assemblies. These models, therefore, require detailed knowledge of the kinetics and mechanisms of environmental attack within the constituent materials of bonded joints as well as across their interfaces. Hydrolysis, oxidation, galvanic or cathodic corrosion are some examples of the damaging mechanisms that can be activated in the presence of moisture.

The core element of the mechanistic approach is to model the rate of environmental-damage processes and to relate them with the mechanical properties of the joint's constituents. Once this information is obtained, stress-based or fracture-based models can be subsequently used to estimate the residual strength and life of aged bonded structures. To date, the attempts to empirically model the rate of environmental attacks have not proved to be very successful [18]. This is mainly because characterising the rate of such chemical reactions in bonded composite joints is very difficult and still in its developmental stage [19].

2.3 Non-mechanistic models

The difference between the non-mechanistic and mechanistic models is that the detailed knowledge of chemical reactions and degradation mechanisms is not required when using the former approach. Instead, the effects of the ageing substance, e.g. moisture, temperature, or UV radiation, on the mechanical properties of the joint's constituents are experimentally characterized. The environmental-dependent mechanical properties are then explicitly related to quantitative parameters representing the ageing substance, for instance moisture content. These material properties will form the basis of the non-mechanistic durability modelling approaches.

A perquisite of any non-mechanistic analysis is to map out the distribution of the ageing substance in different parts of the studied configuration after exposure to certain ageing conditions for a given time. This step is necessary to define the relationship between the obtained material properties and the bonded assembly. This information is usually achieved through thermal or mass diffusion analysis. Once the correct set of mechanical-properties is assigned to the assembly, stress-based or fracture-based models can be used to estimate the strength of the aged configuration. This procedure can be done by using sequentially- or fully-coupled analysis.

Although the non-mechanistic models do not require a detailed knowledge of environmental damage kinetics, they require multi-physics analysis. For this reason, a number of fundamentally different tests are needed to obtain the required input data for various physical models. Some of the limitations of the non-mechanistic models are the lack of consistent test methods, validated test data, and versatile design methods which are needed to obtain quantitative life estimation of bonded composite joints for a given application.

2.4 Correlation factors

This approach uses simple algebraic expressions to correlate empirically obtained strength loss of joints after ageing for relatively short durations with physical or chemical changes caused by a certain ageing substance. Moisture content, color change, swelling, hardness, wear or appearance of cracks are among some of the abovementioned changes. The long-term strength of joints are predicted through extending the obtained correlations from the short-term measurements. The extensions are generally performed by determining an algebraic expression. The most important shortcoming of this approach is the large amount of experimental data that are needed to obtain good correlations, which are only valid for one specific exposure condition.

2.5 Extrapolation of accelerated test data

Accelerated laboratory experiments are the most common type of tests used to assess the durability of bonded joints. These tests are generally used for comparative assessment of different materials and joining methods using extremely harsh conditions. In addition to comparative analysis, the accelerated test results can be used to obtain acceleration factors. An acceleration factor relates degradation and exposure time, and can be used to estimate the life of joints exposed to less damaging natural ageing conditions. However, as the damage progression is accelerated through the use of extremely harsh conditions (such as high temperature), uncontrolled damaging mechanisms might be triggered. This leads to unrealistic degradation levels far greater than those that might be experienced by a joint in service conditions. As a result, the accelerated test results, often, tend to overestimate the degradation of joint strength.

2.6 Summary

The uncertainties associated with the long-term performance of adhesively bonded composite joints used in civil engineering applications is currently compensated by the use of large safety factors. Therefore, there is a need for design methods that account for the effects of environmental ageing conditions during the design phase. Several approaches can be used for predictive modelling of adhesively bonded composite joints exposed to environmental conditions. Among these approaches, the non-mechanistic approach is suitable for numerical modelling, as it directly relates damage to measurable environmental factors.

3 Environmental ageing of bonded FRP/steel joints

3.1 Introduction

Civil engineering structures are generally exposed to a wide range of environmental conditions. Ultraviolet radiation is an environmental factor that is known to affect the strength of composite materials [20]. In bridge applications, however, the FRP composites are usually protected from direct sun exposure, and hence, UV radiation. Hot and wet environmental conditions have also been shown in previous investigations to have deleterious effects on mechanical properties of structural adhesives and FRP composites [21,22]. In addition, the corrosion mechanisms of metallic alloys are accelerated in hot-wet conditions. Therefore, in this chapter, the effects of moisture, which can be in form of humidity, liquid water or de-icing salt solutions, as well as the effects of temperature on bonded FRP/steel joints are briefly discussed.

3.2 Moisture

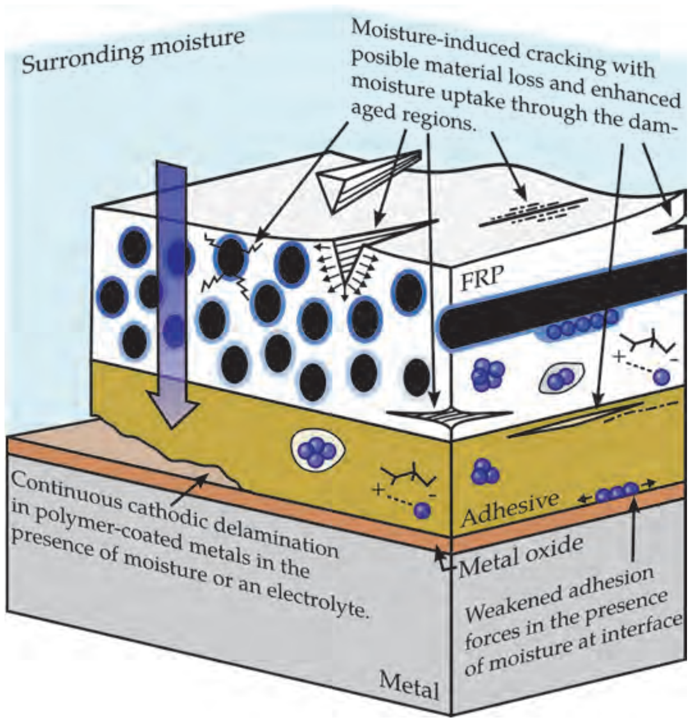

Figure 3.1 *Schematic drawing of the most important moisture-induced damaging mechanism in bonded FRP to metal joints*

Moisture is one of the most problematic substances when discussing environmental durability of adhesive joints with metallic adherends [11]. Many civil engineering structures will inevitably be in direct contact with moisture during their lifetime. This is either due to the design considerations or location, or due to accidental or natural causes. Moisture, can penetrate into adhesively bonded joints by diffusion through the adhesive layer, or wicking along the interfaces, or absorption through the porous adherend [21]. For adhesively bonded joints with impermeable adherends, moisture diffusion through the adhesive layer is the primary route of moisture ingress into the joint. FRPs, however, are permeable materials which can provide shorter moisture ingress routes into the adhesive layer of bonded FRP/steel joints.

As depicted in Figure 3.1, the penetrated moisture can affect joint's mechanical properties through two principal mechanisms [23–26]:

(i) Degradation of adhesive and/or adherends,
(ii) Degradation of adherend/adhesive interface(s).

A review of the literature reveals that the degradation of mechanical properties of structural adhesives and FRP materials have been commonly found to be proportional to their moisture content (see, for example, [27–30]). Therefore, this section provides an overview of the mechanisms of moisture ingress into these materials as well as its damaging mechanisms. Furthermore, the interfacial adhesion in the presence of moisture is concisely discussed.

3.2.1 Mechanisms of moisture ingress

The moisture uptake in polymeric materials, such as epoxies or resin matrix of FRP materials, depends mainly on their chemical composition, and is generally dominated by "diffusion". The word diffusion derives from the Latin word, *diffundere*, which means "to spread out". In chemistry, a substance that "spreads out" is moving from an area of high concentration to an area of low concentration. Therefore, in principle, water molecules move into polymeric materials because of a concentration gradient.

The diffusion process in epoxy adhesives is facilitated due to their surface topology [31] and resin polarity [32]. Soles et al. [31] found that moisture initially penetrates into the epoxy structure through the inherent nano-voids of the epoxy surface topology, which vary from 5–6 Å in diameter. Water molecules have an average diameter of 3 Å and can easily enter epoxies. The polarity of epoxies is due to the presence of hydrophilic groups that attract highly polar water molecules through hydrogen bonding.

In addition to the diffusion of moisture into resin matrix, moisture can enter FRP materials through two other mechanisms [33,34]:

(i) Capillary transport of water molecules along the fibre/matrix interface,
(ii) Penetration into micro-cracks and voids.

Fibre/matrix interfaces provide preferential path-ways for moisture to enter FRP composites. This effect can lead to enhanced moisture ingress in the fibre direction and is often known as the "wicking effect". For example, Pierron et al. [35] reported an extremely larger diffusion rate along the fibre direction than that in transverse to the fibre direction. The existence of voids can also significantly increase the moisture uptake. In this regard, Thomason [36] showed that the presence of only 1% voids, can double moisture uptake compared to a void-free GFRP composite.

The diffusion properties of adhesives and FRPs are essential sets of required data to investigate the effects of moisture on adhesively bonded FRP/steel joints using numerical methods. As the diffusion process in polymeric materials is governed by concentration-gradients, Fick's laws of diffusion are often used to express them [34]. In this context, the simple Fickian model is the most commonly used method [37,38]. However, anomalous diffusion behaviour after the initial moisture uptake has been reported for some adhesives [29,39–41] or FRP composites [39,42–44]. Several models have been proposed to predict such behaviour, including the dual-Fickian (relaxation-dependent) [45,46], the delayed dual-Fickian [47], the concentration-dependent [48], the time-dependent [49], and the

Langmuir model [50,51]. Glaskova et al. [49] investigated the accuracy of a number of these models for a selected epoxy and found the Langmuir and dual-Fickian models more accurate. Figure 3.2 depicts the two diffusion models that are used in this study.

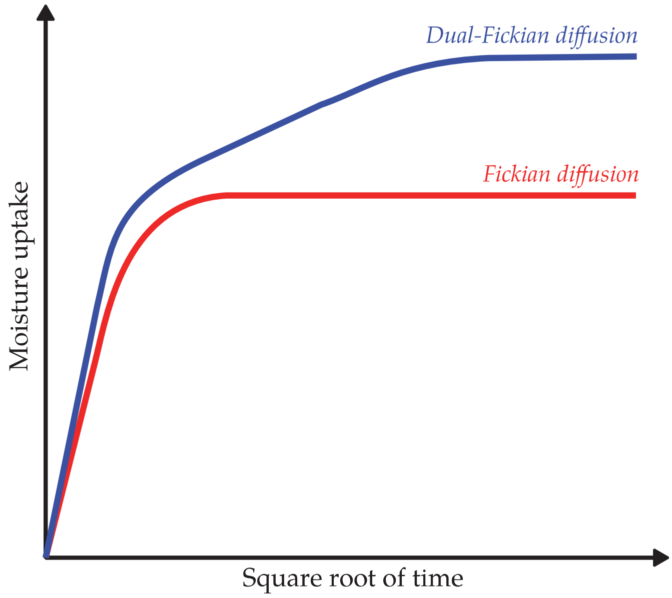

Figure 3.2 *Fickian and dual-Fickian diffusion models*

3.2.2 Effects of moisture on epoxy adhesives and FRP composites

Depending on the polymer structure and chemical composition, the absorbed moisture can lead to physical or chemical changes of adhesives and FRP materials. Physical degradation, which is basically temperature dependent, may dramatically change material properties. However, these changes are reversible and will be recovered upon drying. Chemical degradation, on the other hand, is accompanied with irreversible material changes, and is usually initiated upon longer exposure durations or harsher conditions.

Moisture can alter epoxy adhesives and FRP resins through plasticization, swelling, cracking, and hydrolysis [42,52,53]. Moisture-induced plasticization often leads to severe degradation of modulus of elasticity and strength of polymer adhesives [54–62]. However, as it is thoroughly discussed in **Paper II**, low concentrations of water and subsequently a small amount of moisture-induced plasticization may actually be beneficial at joint-level. Swelling is a consequence of the expansion forces exerted by moisture while stretching polymeric chains, and can lead to internal stresses or cracks in sandwiched structures [63]. The interaction of water molecules with epoxy resins was studied by Zhou and Lucas [64]. Their study showed that depending on the required activation energy for desorption, two types of bound water could be found; Type I or Type II. Type I bound water is manifested by disrupting the weaker inter-chain Van der Waals forces and acts as plasticizer. On the other hand, Type II bound water is a product of strong hydrogen bonds between water molecules and resin network. The amount of Type II bound water, which is harder to remove and causes irreversible material changes, increases with higher temperature and longer exposure time.

Wicking of moisture along fibre/matrix interface of FRP composites can lead to formation of micro-cracks, and thereby loss of integrity [42,65–67]. As outline by Bradley and Garant [68], the transported moisture along fibres initially reduces the strength of chemical bonds at fibre/matrix interfaces. Secondly, matrix subsequent swelling relaxes the existing residual stresses along the fibre/matrix interface, thereby deteriorating interfacial shear strength. The formed micro-cracks also act as new routes for moisture diffusion and accelerate damage growth [65].

FRPs can also undergo degradation at fibre-level. Aramid fibres absorb moisture leading to accelerated fibrillation [16]. As for glass fibres, moisture extracts ions from fibres, which combined with water leads to etching and pitting of the altered-fibre's surface [69]. Carbon is chemically stable at normal temperatures and does not react with water or salts contained in sea water. It should be mentioned that the fibre-level damage is more time-consuming than resin- or interface-level degradation. For FRPs used in civil engineering applications, Karbhari [42] predicts negligible modulus change of the order of 10% over a period of 10-15 years. Matrix-dominated properties, such as interlaminar shear strength, nevertheless, are prone to significantly larger degradations after short-term exposure to humid conditions [70–78].

3.2.3 Effects of moisture on interfacial adhesion

Interfacial debonding is often attributed to premature and sudden failure of adhesive joints. The presence of moisture at interfaces between different constituent materials of bonded joints can cause degradation or loss of adhesion forces. Such forces are generally attributed to the physical adsorption of molecules from the two different materials across the interface via secondary van der Waals forces [79]. Based on this theory, Kinloch [80] showed that while the adhesion between epoxy and FRP materials remained stable after moisture ingression, epoxy/metal interfaces were prone to interfacial debonding in the presence of moisture. This can be explained as follows: the ultra-thin metal-oxide layer that covers the surface of engineering metals attracts highly polar water molecules. The bonds formed between the absorbed moisture and metallic adherends are stronger than the existing van der Waals forces. In addition to reducing the contact area between adhesive and metallic adherend, the interface moisture can exert interfacial stresses upon swelling of the adhesive [81–83].

Corrosion of metallic adherends is another important mechanism that can contribute to interfacial degradation. In general, epoxy-coated metals with conductive surface oxide layers are prone to two main corrosion mechanisms; cathodic and galvanic corrosion [84–87]. Cathodic corrosion begins when an adhesive is in direct contact with an electrolyte. The electrochemical reactions that characterise the continuous cathodic delamination of epoxy/metal interfaces are presented in [88]. Galvanic corrosion occurs when two materials with a sufficient electropotential difference are bridged together in the presence of an electrolyte [89]. The possibility of galvanic corrosion between CFRP and steel has been investigated by some researchers in [90–92] who found that the electropotential difference is large enough for galvanic corrosion to occur.

To improve the interfacial stability of adhesively bonded FRP/steel joints, many researchers have recently proposed various methods of surface preparation and treatment techniques [56,93–101]. In order to maximise the interfacial adhesion, Fernando et al. [93] presented a systematic experimental study to identify proper surface-adhesive combinations for strengthening of steel structures. Grit blasting of steel was found to be a suitable preparation method that leaves a clean and chemically active surface. In addition, silane coupling agents have been shown in a number of studies to improve the bond integrity and its environmental stability by forming primary bonds at steel/adhesive interface, instead of secondary van der Waals forces. Silane can also improve the corrosion resistance of steel adherends by forming a dense multi-molecular siloxane network that is resistant to moisture penetration [56]. Tavakkolizadeh and Saadatmnesh [101] also reported considerable reductions of galvanic corrosion rate in steel–CFRP systems by increasing the thickness of the adhesive layer, which acts as an insulator. The successful application of silane to prevent interfacial failure of bonded FRP/steel joints exposed to harsh environmental conditions is reported by Dawood and Rizkalla in [56].

3.3 Temperature

Elevated temperatures, sub-zero temperature exposure, and temperature variations can affect the performance of FRPs and FRP rehabilitated structures. It is generally accepted that the resin matrix, adhesive and fiber/matrix interface are the most susceptible components of adhesively bonded FRP/steel joints to thermal effects.

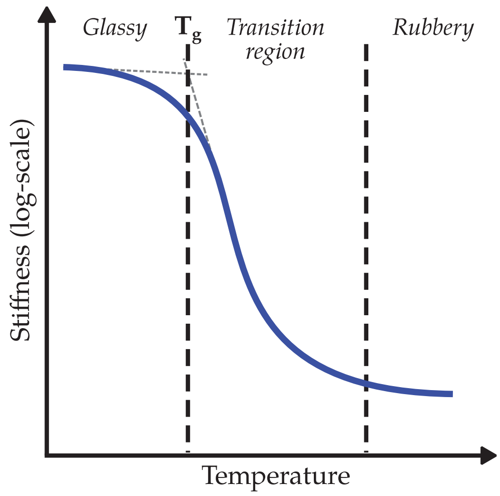

Figure 3.3 *Definition of glass transition temperature, T_g*

Increasing the temperature can alter the state of thermosetting materials, such as epoxies, from an initially hard, rigid or "glassy" state to a more pliable, compliant or "rubbery" state. The onset of these changes is known as glass transition temperature (T_g), see Figure 3.3. In this context, the temperature ranges from slightly below T_g to higher values are referred to as elevated temperatures. Exposure to elevated temperatures can lead to increased viscoelastic response of adhesives and resins. This is accompanied by significant loss of stiffness and strength of bonded FRP/steel joints as well as an increased moisture absorption susceptibility [16]. On the contrary, exposure to temperatures below T_g and above room temperature (RT) is advantageous as it can result in further post-curing [102,103]. It should be noted that T_g of epoxies is strongly dependent on the curing conditions; curing at elevated temperatures can result in higher T_g than that of the same material cured at room temperature. This phenomenon is believed to be the reason for the improved environmental-durability of FRP/steel joints cured at elevated temperatures tested by Nguyen et al. [104].

Sub-zero temperature exposure can lead to FRP matrix embrittlement, matrix hardening, matrix micro-cracking, fibre/matrix bond degradation, and increased risk of interfacial debonding. These responses are caused by changes in the FRP constituents at low temperatures, or due to the incompatibility of coefficients of thermal expansion (CTE) of fibres and resin or steel and adhesive. As a result of the latter, shear stresses are formed at the interfaces, which combined with increased matrix or adhesive embrittlement can lead to formation of micro-cracks along adhesive/steel or fibre/matrix interfaces. Although, the magnitude of these stresses is generally lower than the strength of resin or adhesive material [105], their repeated appearance under freeze/thaw cycles can be more detrimental. Furthermore, the presence of trapped water inside the existing cracks and voids of matrix or adhesive, which induces severe stresses upon volumetric expansion due to freezing, can lead to the formation of additional micro-cracks [106,107]. The effects of exposure to sub-zero or freeze/thaw cycles are illustrated in Figure 3.4.

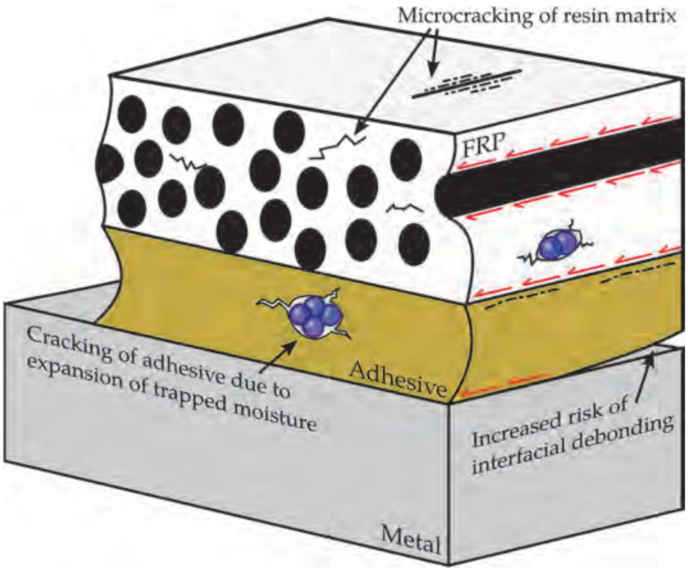

Figure 3.4 *Effects of sub-zero and freeze/thaw cycles on bonded FRP/steel joints*

3.4 Research needs

Although there is a wealth of literature on the effects of moisture and temperature on adhesives and composites, the majority of tests have been conducted in engineering fields, such as the aerospace and automotive industries, which have distinct differences compared with civil engineering applications [15,16]. Curing conditions, operating environments, and material production and formulations are some examples of the aforementioned dissimilarities. There is, therefore, a need to conduct long-term durability tests utilizing service exposure and materials of relevance to civil engineering applications. Another limitation of the existing research is that the bonded joints tested in the aforementioned disciplines are usually made of aluminium adherends. Aluminium is moisture impermeable which could create a completely different state of moisture distribution in aged bonded joints.

The adhesive layer thickness is another factor which can significantly affect the outcome of durability investigations by influencing the interfacial damage mechanisms, such as galvanic or cathodic corrosion. The thickness of adhesive layer of joints found in bridges is usually 1–6mm which is significantly larger than the 0.1–0.25mm thick adhesive layers found in car or aviation applications. However, the majority of the available studies have used adhesive layers that are orders of magnitude thinner than those used in bridges. For this reason, the joint-level configurations used in this study were designed to have two adhesive layer thicknesses, which are representative of different applications of adhesive joints in bridges.

Adhesively bonded joints used in outdoor applications, such as bridges, are often exposed to aggressive environments. The combined effect of these service conditions may be more damaging than the adverse effect of each individual condition. The review of current studies is evidence of a lack of systematic long-term experiments aimed at clearly identifying the individual and combined effect of each environmental parameter at joint-level. To address this issue, the conducted experiments in this study were designed to characterise the combined and isolated effects of moisture (saltwater, distilled water or relative humidity) and temperature under constant or cyclic exposure conditions.

4 Design and failure prediction of bonded joints

4.1 Introduction

The failure of adhesively bonded FRP/steel joints may take place in one, or a combination, of the following modes, as shown in Figure 4.1:

(i) Cohesive failure within the adhesive layer,
(ii) Debonding at steel/adhesive or FRP/adhesive interfaces, or
(iii) Delamination in FRP, which is characterized by interlaminar shear strength of the FRP material.

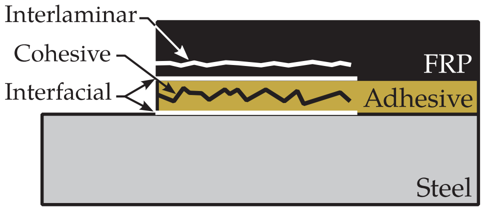

Figure 4.1 *Possible failure modes of bonded FRP/steel joints*

The rupture of the FRP laminate is an additional failure mode which can occur if the aforementioned failure modes could be prevented. Which failure mode governs the strength of FRP/steel joints depends on several parameters, including the through-thickness strength of the FRP material, the geometry of the joint (see, for example, [108,109]) and the quality of surface preparation. In addition, as it was discussed in Section 3, environmental ageing can affect the constituents of these joints differently, which can alter the failure mode of aged joints. Therefore, to accurately analyse the failure of such joints, it is essential to consider approaches that are applicable to different failure modes.

Environmental ageing can result in non-uniform moisture/environmental-damage distribution profile in adhesively bonded FRP/steel joints (see **Papers II**, **IV** and **VI**). This puts another requirement on the analysis and design method when the effects of environmental ageing need to be accounted for. As the conventional design methods, such as the stress/strain based methods are not suitable for such complex situations, alternative design approaches are needed.

Recently, a great deal of interest has been shown in using the damage mechanics approach for strength prediction of structural adhesive joints, see, for example, [110–115]. One of the techniques in the damage mechanics approach is the cohesive zone modelling, which offers several advantages over traditional approaches. The aim of this chapter is to provide some fundamental aspects of the cohesive zone modelling.

4.2 Cohesive zone modelling

The founders of cohesive zone modelling (CZM) are Barenblatt [116] and Dugdale [117]. Barrenblatt introduced cohesive stresses to circumvent stress singularity problems at the crack tip predicted by an elastic stress analysis. The cohesive stresses were assumed to be acting on two crack surfaces located within a small region ahead of the crack tip, referred to as fracture process zone. Dugdale assumed constant cohesive stresses across cohesive zone to estimate the size of the plastic zone at the crack tip in metals. This method was further developed by Hillerborg et al. [118] to study crack growth in concrete. Needleman

[119] was first to introduce the CZM in a finite element context. Since then, finite element analysis using CZM have been used to predict fracture in a wide range of engineering applications including adhesively bonded joints [120], delamination of FRPs [121], and bimaterial interfaces [122]. Cohesive elements were implemented in version 6.5 of Abaqus® and are nowadays available in most commercial finite element software.

The basic idea of CZM is that microscopic damage is simulated along a pre-defined crack path. By doing so, the stress singularity at the sharp crack tip is replaced with a fracture process zone, where the damage caused by the stress field reduces the material strength. In other words, the fracture formation is considered as a gradual process in which the separation of the crack surfaces takes place across an extended crack tip, or cohesive zone, and is resisted by cohesive stresses. This model is depicted in Figure 4.2 for a cracked structure loaded in pure Mode-I, after [123]. The undamaged material is assumed to have a finite tensile strength equal to $\hat{\sigma}_n$. At a certain distance from the crack tip, or stress raiser, the stress increases to $\hat{\sigma}_n$. Hillerborg [124] denotes this position as the head of a fictitious crack, which is an extension of the macroscopic crack tip by the length of the fracture process zone, L. As the material within fracture process zone $(\text{-}L \leq x_1 < 0)$, undergoes damage, its ability to transfer stresses reduces and the fictitious crack opens, δ_n. The weakening of the material continues with increasing opening until the critical end-opening value, δ_n^*, is reached. At this point the material becomes completely damaged at the crack tip, or stress raiser, $x_1 = \text{-}L$. The completely damaged material does not transfer stresses anymore, which indicates the formation of new crack surfaces. This process is simulated in cohesive zone models by using "cohesive laws". A cohesive law provides the relationship between the cohesive stresses (tractions) and separations along fracture process zone.

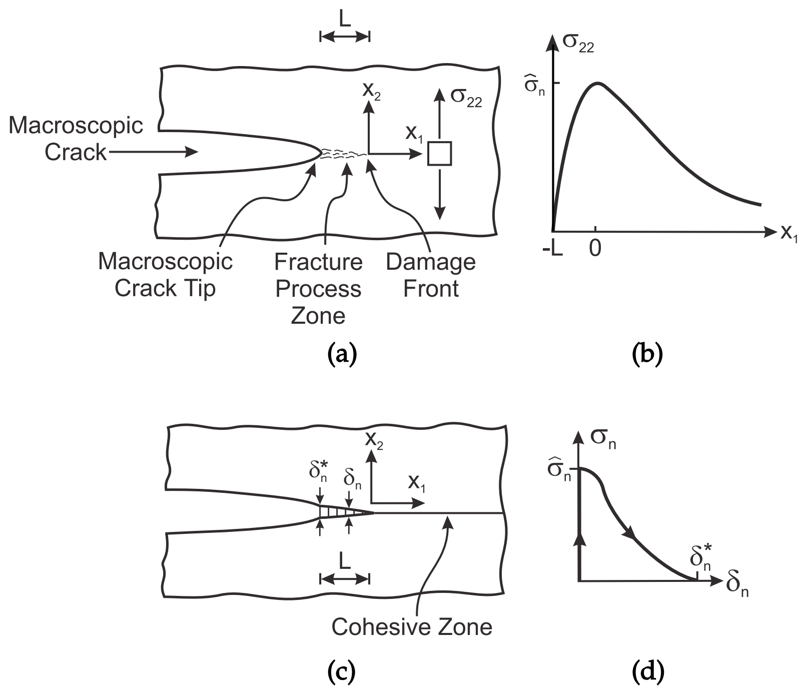

Figure 4.2 *Representation of a fracture process zone with initial zero thickness by a cohesive law: (a) the physical problem, (b) stress distribution ahead of the crack tip, (c) cohesive zone model, (d) cohesive law (slightly modified from* [123])

Cohesive laws relate stresses to separations. Consequently, they automatically include an energy-based propagation criterion inherent to fracture mechanics principles. In this regard, the total area under a cohesive law is equivalent to the work required to produce fracture, also known as fracture energy (J_c).

A notable advantage of the CZM, which has been outlined by many researchers, is its wide range of applicability. This is mainly because the CZM incorporates a damage initiation criterion (i.e. no need of initial cracks) as well as an energy-based propagation criterion. Stress/strain-based models are not suitable when fracture emerges from the locations of stress singularity, such as bi-material interfaces or sharp corners. Methods based on the linear elastic fracture mechanics, LEFM, are only useful when an initial crack is present. In addition, as it is discussed in Section 4.2.1, the LEFM method is not applicable to materials with ductile fracture. The CZM does not suffer from these restrictions, and hence, is suitable to model fracture of complex structures such as environmentally aged adhesively bonded joints [61]. The application of the CZM to model the fracture of adhesively bonded FRP/steel joints is thoroughly discussed in **Paper III**.

4.2.1 Fracture process zone

As discussed before, fracture process zone (FPZ) is the region at the proximity of a crack tip where inelastic processes such as plastic deformation and micro-cracking take place. The adhesive layer in adhesively bonded joints is often regarded as a macroscopic crack. In modelling the structures with cracks, the size of FPZ determines whether or not it is necessary to consider the existence of a cohesive zone. This is of particular importance when deriving the cohesive laws of a material from experiments.

It is assumed in the LEFM that specimen deforms mainly elastically. Given the inelastic nature of processes at FPZ, the LEFM is only applicable if the length of FPZ is small compared to the specimen size. Under this condition, the stresses outside the FPZ and in the vicinity of the crack tip approach the stress field of LEFM, see Figure 4.3. This region is

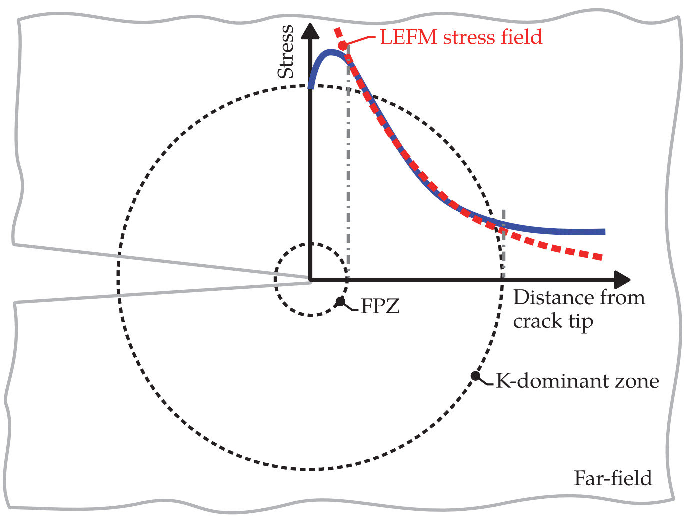

Figure 4.3. Illustration of *different zones at crack tip*

denoted the *K-dominant* zone. Regardless of the specimen size, geometry and loading configuration, the stresses within the K-dominant zone can be obtained by stress intensity factor, K [125]. Far from the FPZ, the stress field is determined by the shape of the specimen and the loading conditions. Within the FPZ, the stress field is governed by cohesive tractions obtained from the cohesive laws. If the size of the FPZ is smaller than the K-dominant zone, a critical stress intensity factor can be used as a crack growth criterion, which makes the damage progression in FPZ, i.e. cohesive laws, unimportant. Modern adhesives, however, are generally formulated to undergo large deformations prior to fracture, a consequence of which is the formation of a large FPZ ahead of the crack tip. In such conditions, the size of FPZ is often considerably larger than the size of the K-dominant zone. As a result, the stresses ahead of the crack are no longer controlled by the LEFM stress field and become dependent on the specimen geometry. This violates the assumption of small-scale FPZ of the LEFM. Hence, cohesive zone modelling, using cohesive laws as the correct material properties, should be preferred. In addition, experimental characterisation of cohesive laws should be performed using methods that are not based on small-scale FPZ. This can be achieved by using the *J-integral*.

4.2.2 J-integral

In 1968, Rice [126] developed a method to characterise nonlinear material behaviour ahead of a crack. The characterisation of the local deformation field near cracks or other stress raising features is a complicated process. This is mainly because the material in this region usually undergoes substantial nonlinear deformations. To circumvent this problem, Rice introduced a two-dimensional path-independent line integral, which he called the J-integral [126]. Using the path independency of the J-integral, he showed that the local deformation field near a crack tip can be determined by studying the remote stress, strain and displacement fields that are easier to obtain. In other words, the J-integral evaluated around the FPZ and around the external boundaries yield the same value, see Figure 4.4, and is given by:

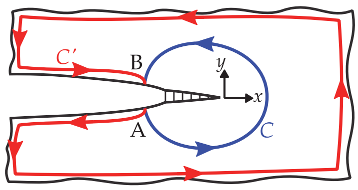

Figure 4.4 *Path-independency of the J-integral*

$$J = \int_C \left(\sigma \mathrm{d}\varepsilon \mathrm{d}y - \mathbf{T}.\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}x}\mathrm{d}C \right) \tag{4.1}$$

where C is any arbitrary counter-clockwise integration path, σ and ε denote the stress and strain tensors, and $\mathbf{T}$ and $\mathbf{u}$ the traction and displacement vectors, respectively.

Rice [126] showed that the value of this integral for a cracked body subjected to quasi-static loading is equal to the energy release rate, G. By idealizing elastic-plastic deformations as nonlinear elastic, he was able to generalize the energy release rate to nonlinear materials, and thus, extending fracture mechanics methodology well beyond the validity limits of the LEFM.

For a monotonically loaded adhesively bonded joint, Högberg et al. [127] evaluated Eq. (4.1) along a contour encircling the crack tip and derived:

$$G = \lim_{C \to 0} J_C = \left(\int_0^w \sigma \mathrm{d}w + \int_0^v \tau \mathrm{d}v \right)_{x=0} \tag{4.2}$$

where w and v are normal and shear deformations of the adhesive layer at crack tip (x=0). This equation shows that the evaluated J-integral represents the work of the cohesive tractions under Mode-I and Mode-II cohesive laws. Furthermore, Sørensen and Kirkegaard [128] showed that by continuous measurement of the J-integral and peeling or shear deformations at the crack tip, the cohesive laws could be determined by differentiating Eq. (4.2) as follows:

$$\sigma(w,v) = \frac{\partial J_C(w,v)}{\partial w}, \qquad \tau(w,v) = \frac{\partial J_C(w,v)}{\partial v} \tag{4.3}$$

4.3 Characterisation of cohesive laws

The measurement of cohesive laws, as material models, is essential for successful application of the CZM. Such measurement methods, however, have been the subject of less research compared to the extensive development of the CZM numerical models. The fracture test methods provided in the current standards have been developed within the context of linear elastic fracture mechanics, LEFM (such as, ASTM D3433 [129]). However, as discussed before, the application of the LEFM to materials with large FPZ can be accompanied with substantial error (see, for example, [130]). In this section, a brief overview of the methods that have been proposed for characterisation of cohesive laws is presented.

The most straightforward experimental approach to characterise the cohesive laws is the pure tensile or shear testing methods using coupon specimens. In this method, the applied stress at the ends of specimen and the opening displacement on both sides of the damaged zone are measured [131]. Practical difficulties associated with this method are to obtain stable cracks as well as uniform separation and stress distribution across the specimen width [132].

Another method is the so-called "inverse method", which is based on numerical simulations of tested specimens. In this method a number of incremental finite element simulations with varying cohesive law are conducted. The cohesive law that gives the best fit to experimental measurements, usually the load-displacement curve [133], is taken as the "true" cohesive law. A drawback of this method is that the shape of cohesive law is not identified experimentally, which limits the accuracy of the characterised cohesive laws to that of the assumed trials.

Recently, a method based on the J-integral has been used to directly characterise the cohesive laws of a specific material or interface from experiments [134–140]. This approach is called the "direct method" and requires the simultaneous measurement of the end-opening of the crack, and the J-integral value. The cohesive laws are derived by the differentiation of the energy release rate with respect to the separation at the crack tip, cf. Eq. (4.3). The experimental measurement techniques and numerical data reduction schemes for the direct method are presented in **Paper V**.

4.4 Summary

- Cohesive zone modelling is a versatile method that can be used to predict the failure of adhesively bonded FRP/steel joints with various possible failure modes. When using the CZM, both the damage initiation and propagation procedures are modelled. Hence, it can be used to overcome the need for an initial crack in the LEFM, and stress singularity problems of stress-based approaches.
- Modern adhesives are formulated to undergo large deformations prior to fracture. As a result, the size of fracture process zone ahead of crack often becomes significant compared to other dimensions of the specimen. Under these circumstances, the LEFM method is no longer valid, and the FPZ should be modelled by a cohesive zone.
- The direct method based on J-integral is used in this thesis to directly characterise the cohesive laws of a ductile epoxy adhesive from experimental measurements.

5 Overview of the experimental programme

Figure 5.1 shows the flowchart of the experimental programme, which was divided into two main branches:

(i) Experiments aimed at characterizing the environmental effects at material-level,
(ii) Experiments aimed at studying the behaviour of environmentally aged joints.

The material characterization tests were designed to obtain moisture diffusion as well as environmentally dependent mechanical properties of the constituent materials of FRP/steel joints. Standard gravimetric measurements were modified and used to obtain 1D and 3D diffusion characteristics (**Paper II** for constant exposure and **Paper VI** for cyclic exposure). Standard tensile material coupons were used to investigate the effects of aging on tensile properties of the adhesive material and FRP composites (**Paper IV** for constant exposure and **Paper VI** for cyclic exposure). The dependency of the Mode-I and Mode-II cohesive laws of the adhesive material on environmental ageing was studied using open-face double cantilever beam (DCB) and end notched flexure (ENF) specimens, respectively (**Paper V**). The outcome of these tests served as the input data for the numerical analysis.

In order to investigate the long-term performance and identify the environmental damaging mechanisms at joint-level, adhesively bonded CFRP/steel and GFRP/steel double lap shear (DLS) joints were manufactured. The advantage of the DLS configuration compared to the other commonly used joints is the ease of failure detection and relatively straightforward testing procedure. In addition, the stress state at the outer ends of the bond line in a DLS specimen is very similar to that of steel girders strengthened with FRP laminates [141]. The adhesive layer thickness of these specimens were designed to represent typical field applications of bonded FRPs in bridges. More importantly, this test series were used to verify the FE analysis predictions of environmentally aged joints. Therefore, in the planning of the test matrix, special consideration was given to include sufficient testing intervals and exposure combinations. In this regard, the following exposure scenarios were included:

(i) Water immersion vs. high relative humidity levels,
(ii) Exposure to de-icing salt solutions likely to occur in bridges,
(iii) Temperature as an accelerating factor compared with ambient temperature conditions,
(iv) Cyclic wet/dry exposure scenarios,
(v) Freeze/thaw cycles in the absence/presence of moisture/de-icing salts.

In the design of the experiments, special consideration was given to avoid activating unrealistic damaging mechanisms at high temperatures. Therefore, in addition to the abovementioned experiments, the glass transition temperature (T_g) of the adhesive materials was measured using dynamic mechanical analysis (DMA). The DMA tests were carried out on three epoxy adhesive specimens using a TA Instruments® DMA Q800 machine, see Figure 5.2. The oscillatory strain amplitude of 0.01 % was applied at a frequency

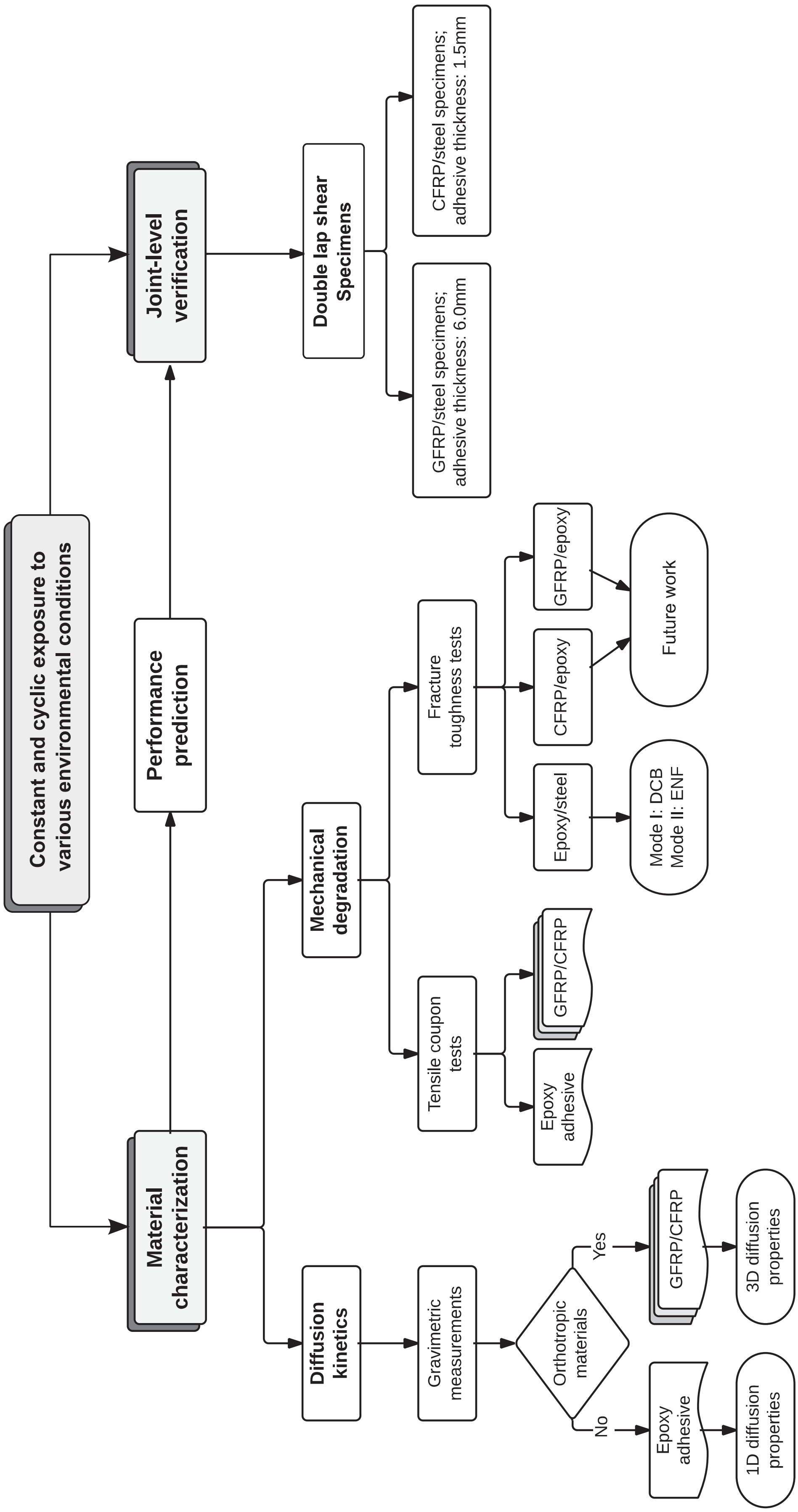

Figure 5.1 *Flow chart of the experimental programme*

of 1 Hz on a tensile setup while the sample was heated up at a rate of 2 °C/min from 25 °C to 100 °C. The average results for all specimens are plotted in Figure 5.3. It can be seen that the onset of storage modulus loss is at 55 °C, while the peak of *tan(δ)* is found at 65 °C. Although both of these values can be interpreted as T_g of adhesive, the former is more meaningful from a mechanical perspective. Thus, T_g = 55 °C was considered for the adhesive, and the exposure scenarios were designed to have at least 10 °C margin as recommended in [142,143].

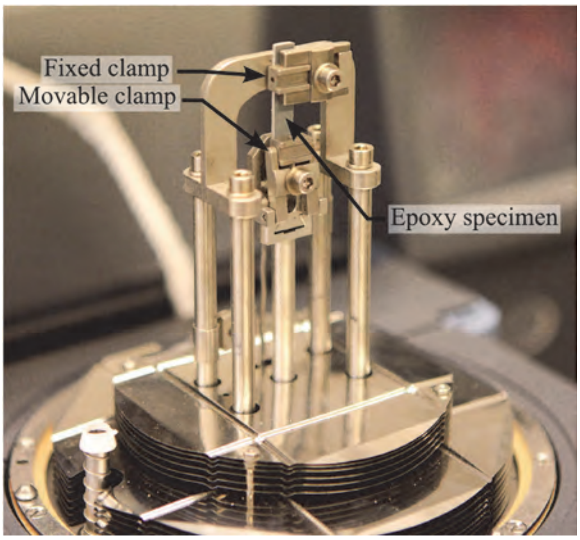

Figure 5.2 *Clamped specimen inside the furnace of DMA testing machine*

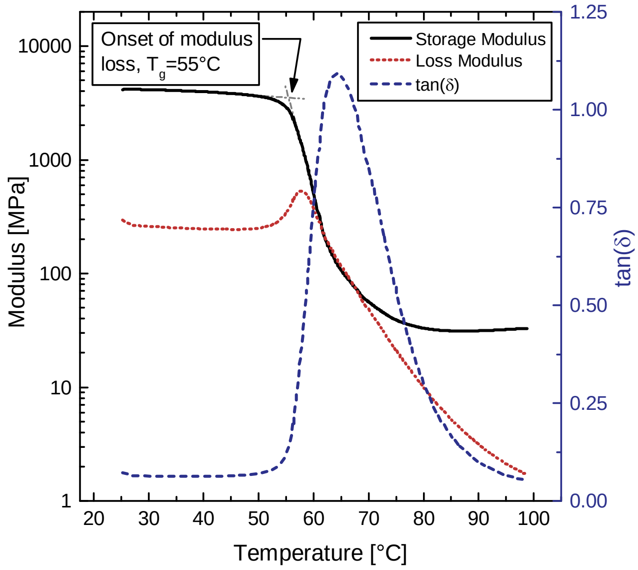

Figure 5.3 *DMA test results of the adhesive material*

6 Summary of appended papers

On the basis of the previous chapters, a framework for long-term performance assessment of bonded FRP/steel joints was developed. The appended papers include thorough documentation of this work. In this chapter, the content of each paper is briefly summarized.

Paper I: "Environmental durability of adhesively bonded FRP/steel joints in civil engineering applications: State of the art"

A literature review of the effects of moisture and temperature, as the most important environmental factors, on the long-term performance of bonded FRP/steel joints used in bridge applications is presented in this paper. At material-level, the collected test results of the effect of moisture on the mechanical properties of the most commonly used structural adhesives and resins showed a clear correlation between the elastic modulus and tensile strength with moisture content. The failure strain, on the other hand, did not exhibit a clear trend with increasing moisture content.

This paper also includes the review of the most relevant literature focusing on the joint-level damaging mechanisms. Particular attention was paid to the interfacial adhesion in the presence of moisture. The available experimental results revealed noticeably superior performance of joints made with grit-blasted steel adherends treated with coating agents, such as silane, compared with grit-blasted-only series. As can be seen in Figure 6.1, the strength reduction rates of joints with interfacial failure mode are clearly larger than specimens with other failure modes. Another observation from this figure is the relatively short exposure durations of the available long-term experiments compared with the service-life of civil structures. Thus, there is a need for tests with ageing durations of at least 18 months, as suggested by Karbhari et al. [16]. Similar to moisture, thermal cycles were found to be the most damaging to joints suffering from weak steel/adhesive interfaces. No study was found to address the effect of freeze-thaw cycles on strength of joints that contain moisture.

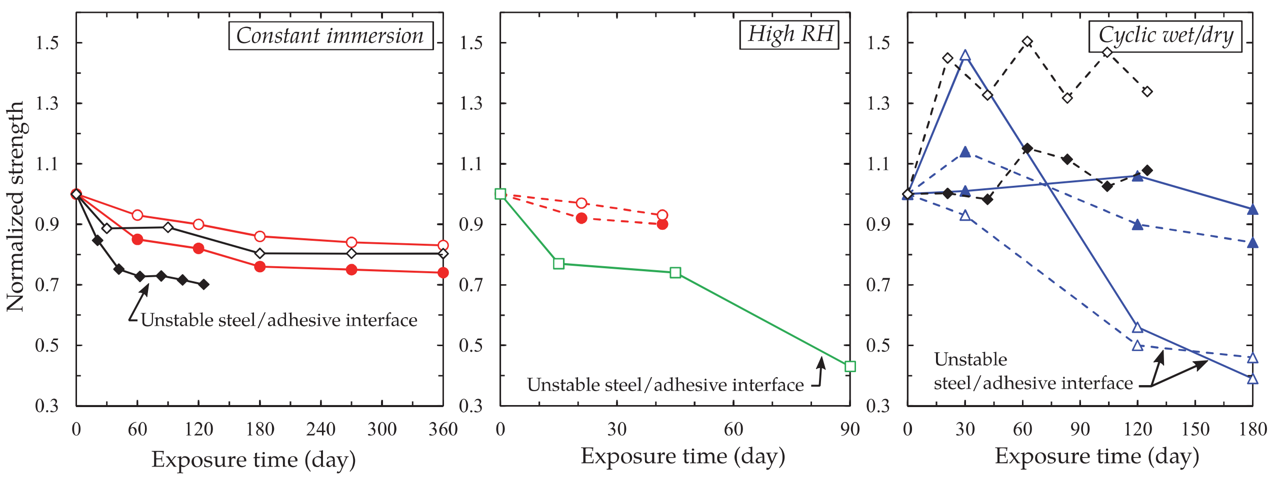

Figure 6.1 *Strength variation of bonded FRP/steel joints with increasing moisture exposure duration in humid conditions; experimental data from Refs.* [56,144–147]

Paper II: “Effects of Moisture on the Long-term Performance of Adhesively Bonded FRP/steel Joints Used in Bridges”

In **Paper I** moisture was identified as the most important factor affecting the durability of bonded joints. Therefore, in this paper, moisture diffusion into bonded joints with permeable adherends, and its consequences on the long-term performance of FRP/steel joints were investigated. Gravimetric experiments were utilized to obtain the moisture diffusion characteristics of GFRP and CFRP composite materials, as well as epoxy adhesive. The GFRP material was found to be highly permeable in immersion condition, which was believed to be due to its low fibre volume, type of resin material, and stack layup. The same material, however, hardly absorbed any moisture when exposed to high relative humidity conditions. The characterised diffusion properties were used as input data for mass diffusion FE analysis to predict the moisture distribution in joints with different FRP adherends and adhesive layer thicknesses, see Figure 6.2. As can be seen, the moisture diffusion into the bond-line of the DLS joint made with GFRP adherends is considerably accelerated. This might lead to several issues that are discussed in **Paper IV**.

Having obtained the moisture-concentration profile in the DLS joint, it is possible to define the mechanical properties of the adhesive as a function of moisture content to determine the load transfer and the stress distribution in the joint. This was achieved by using

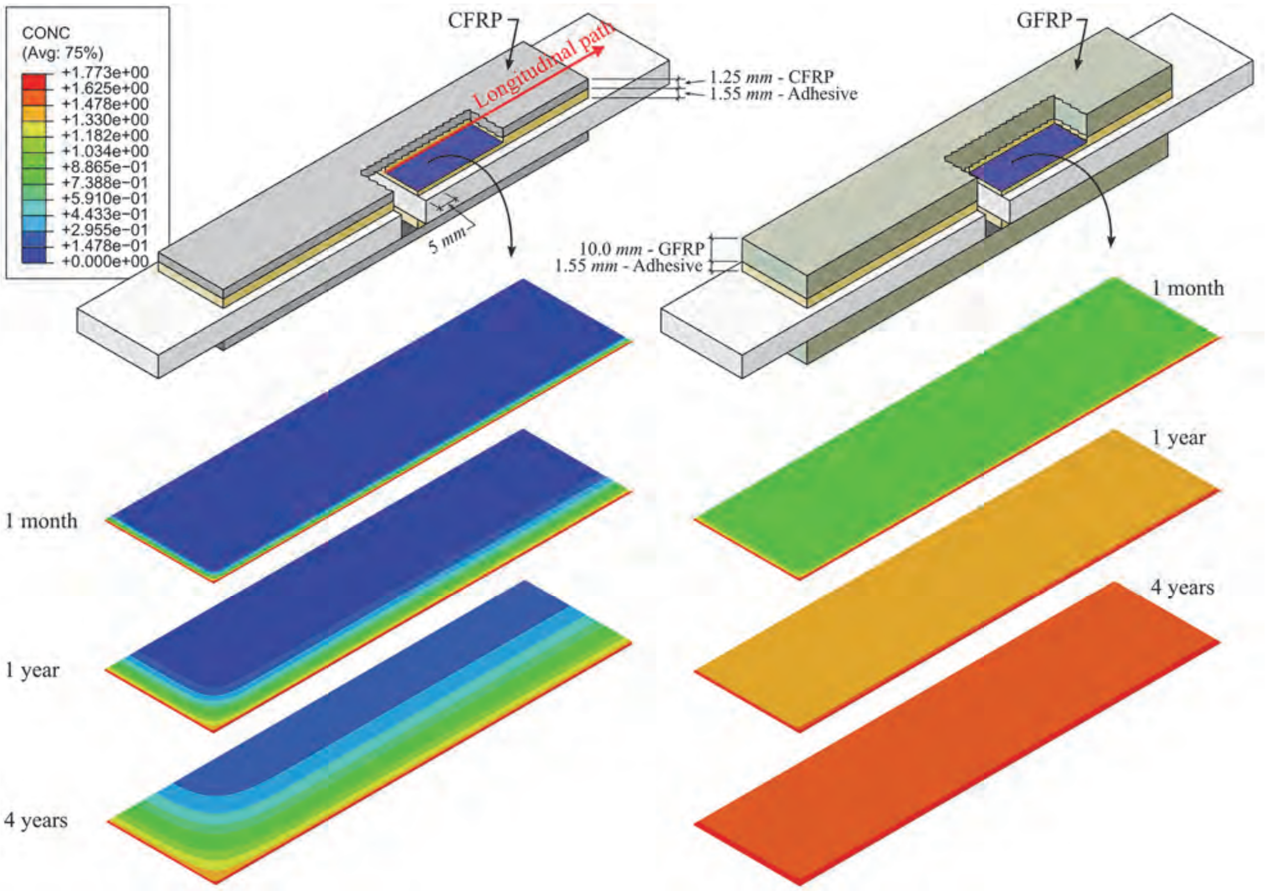

Figure 6.2 *Predicted moisture-concentration profiles in the adhesive mid-layer of DLS joints immersed in distilled water at 45°C: (a) DLS with CFRP, (b) DLS with GFRP*

a sequentially coupled diffusion-mechanical analysis, in conjunction with experimental characterisation of moisture-dependent mechanical properties of the adhesive material. The results are plotted in Figure 6.3, which clearly show a reduction of the normalized maximum principal stress in the adhesive layer with increasing immersion time in distilled water at 45°C. In order to verify this observation, a number of DLS specimens were aged under the same conditions for up to a year and tested at various intervals. The results indicated that moisture could be beneficial on the strength of joints with cohesive failure. This observation was attributed to the reduction of peak stresses in the adhesive layer predicted by the FE simulations. However, extending the exposure duration shifted the failure locus to the interface with steel, and was accompanied with ca. 9% reduction in joints' load-bearing capacity.

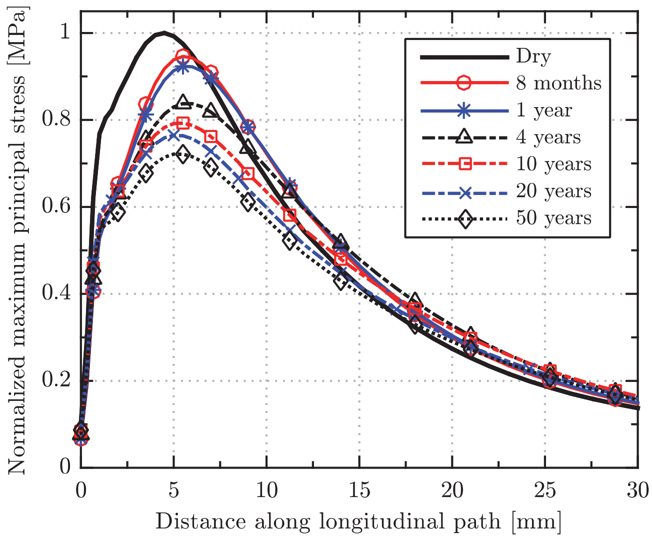

Figure 6.3 *Normalized maximum principal stress in the adhesive mid-layer of a DLS joint with CFRP adherends conditioned in distilled water at 45°C*

Paper III: "On the design of adhesively bonded FRP-steel joints using cohesive zone modelling"

As it was discussed in Chapter 2, predictive durability-modelling approaches, such as non-mechanistic models, are required to function in conjunction with appropriate structural assessment methods. Therefore, the aim of this paper was to provide new insight into the design of adhesively bonded FRP/steel joints using cohesive zone modelling. In this regard, the dependency of the predicted strength of joints on parameters such as shape and type of cohesive law, crack path location, length of fracture process zone, variations of adhesive and FRP properties, and different failure modes including cohesive, interfacial debonding and FRP failure were investigated.

In general, the predictions were found to be in good agreement with the experimental results provided that all possible failure modes are simultaneously taken into account. For instance, the best prediction for behaviour of DLS specimen was obtained when the combined cohesive/interfacial failure mode was considered in the model, see Figure 6.4. In addition, the cohesive laws obtained using the direct approach were found to accurately represent the damage evolution and fracture in the adhesive layer. As can be seen in Figure 6.5, unlike Mode-I fracture energy which had no impact on the predicted joint strength, variation of Mode-II fracture energy influenced the predicted joint strength to a large extent. Moreover, the effective overlap length was found to be in direct correlation with the length of fracture process zone in the adhesive layer. Hence, the knowledge of damage evolution provided by the CZM can be advantageous during the design phase to ensure a sufficiently long anchorage length and to account for the effect of environmental parameters such as temperature and moisture.

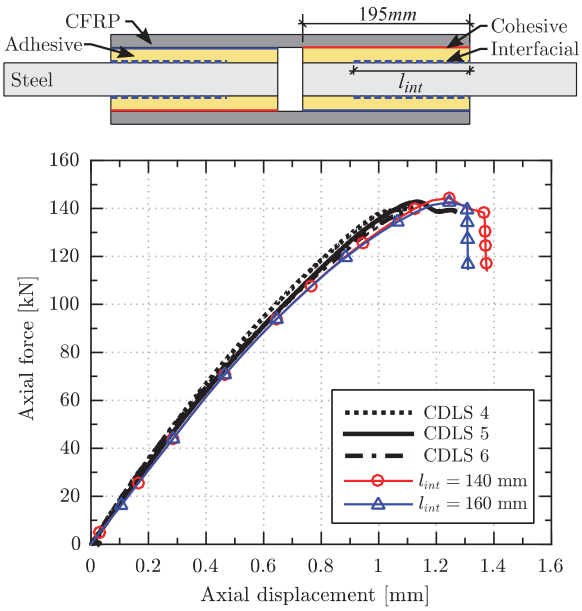

Figure 6.4 *Effect of combined interfacial/cohesive failure on load-displacement response of DLS joints*

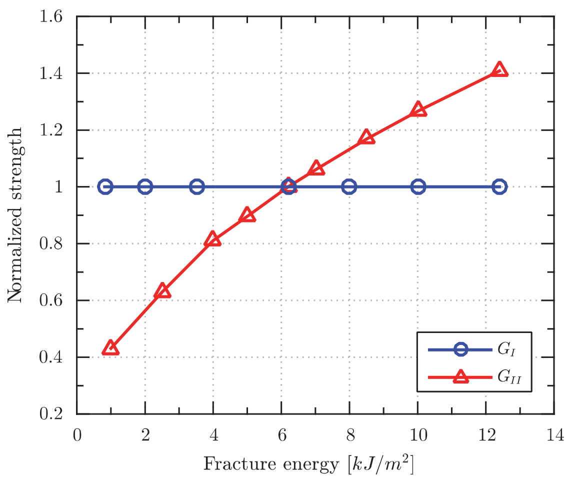

Figure 6.5 *Effect of mode I and mode II fracture energy on the predicted strength of DLS joints*

Paper IV: "Durability of bonded FRP-to-steel joints: effects of moisture, de-icing salt solution, temperature and FRP type"

The experimental results of 192 specimens after ageing for up to three years under constant exposure to various environmental conditions are presented in this paper. This study was designed to complement the existing knowledge regarding the durability of adhesively bonded FRP/steel joints as suggested in **Paper I**. This was achieved by utilizing exposure durations longer than 18 months, joints with adhesive layer thicknesses and FRP materials similar to those used in bridge applications, differentiating the effects of each environmental factor (i.e. moisture, temperature and salt solution) on joint durability, and predicting the moisture distribution profile in aged specimens at the time of testing (using the methodology described in **Paper II**). The test setup of DLS specimens is depicted in Figure 6.6.

Experimental results showed that environmental ageing had different effects on the DLS joints depending on the used FRP adherend. For the case of CFRP/steel joints, while ageing at room temperature did not have any adverse structural effects, immersion at 45°C was found to be detrimental. In this regard, salt-water immersion was found to severely damage the interlaminar shear strength of the CFRP material, which led to a maximum strength reduction of 43% at joint-level. The GFRP/steel joints, on the other hand, developed irregular longitudinal cracks in their adhesive layer after approximately one year of immersion at 45°C, see Figure 6.7. These cracks are believed to be a result of through-thickness stresses due to swelling in the adhesive layer caused by high permeability of the GFRP adherend and, hence, the accelerated moisture diffusion.

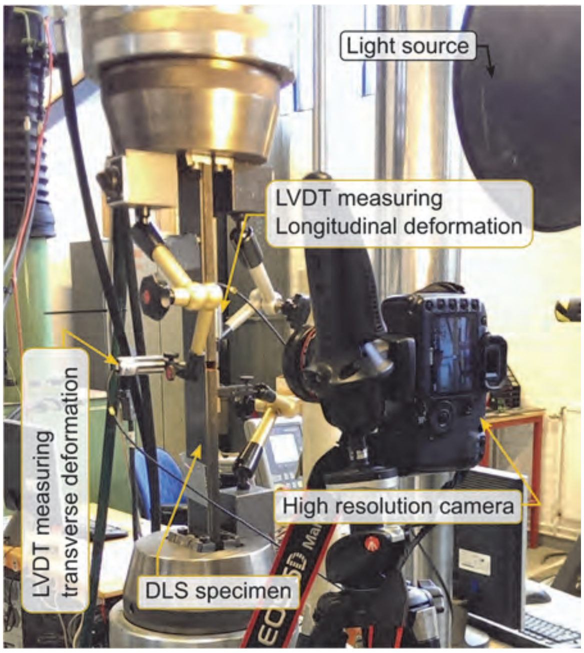

Figure 6.6 *Test setup of DLS specimens*

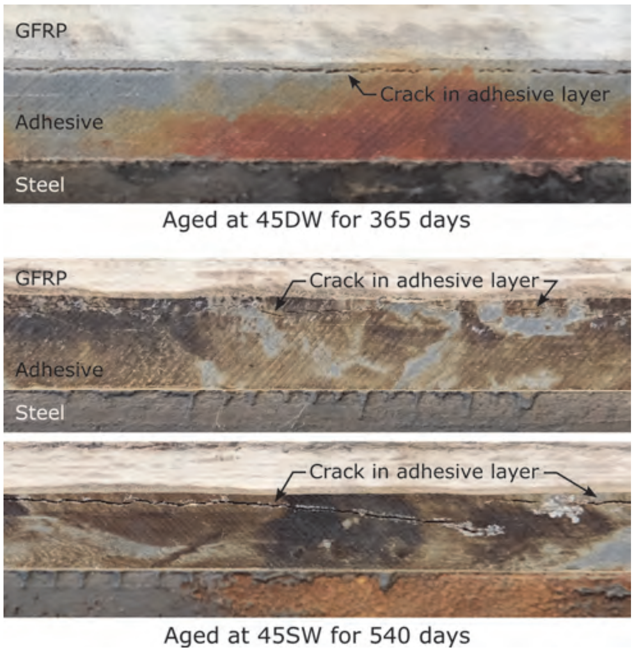

Figure 6.7 *Appearance of cracks in the adhesive layer of GFRP/steel DLS specimens; 45DW and 45SW: distilled water and salt-water at 45°C, respectively*

Paper V: "Dependency of cohesive laws of a structural adhesive in Mode-I and Mode-II loading on moisture, freeze/thaw cycling, and their synergy"

Accurate measurement of cohesive laws is the perquisite of the developed model in **Paper III** for the design of adhesively bonded FRP/steel joints. In addition, by knowing the dependency of cohesive laws on environmental factors, this model can be coupled with the moisture diffusion analysis described in **Paper II** to predict the mechanical behaviour of aged joints. Therefore, in this paper a direct method for derivation of environmental-dependent cohesive laws of an epoxy adhesive was developed. Special attention was given to achieve uniform moisture distribution in the adhesive layer in relatively short time.

Figure 6.8 illustrates the overview of the used methodology in this paper. Open-face specimens were manufactured to overcome long exposure durations usually needed to reach moisture saturation. These specimens were exposed to a number of constant and cyclic environmental exposure scenarios, after which the cohesive laws were derived directly from measurements. The "open specimens" were completed prior to testing by bonding the second steel adherend using a secondary adhesive material. The simulation of experiments showed that the adopted method can yield accurate results if the secondary adhesive layer is thinner, less stiff and stronger than the primary adhesive.

Environmental ageing was found to influence Mode I and Mode II cohesive laws of the studied epoxy adhesive differently. For both loading modes, however, the reductions of fracture energy were found to be the largest for saltwater, and not directly proportional to the moisture content of the adhesive layer. For Mode II loading, larger critical deformations were observed with increased moisture content. Hence, the critical fracture energy (area under cohesive law) was less severely affected as compared with that of Mode I. The comparison of degradations of the peak stress of cohesive laws with tensile strength of adhesive dog-bone specimens exposed to the same wet conditions (characterised in **Paper IV**) revealed the improperness of the latter method when used to obtain traction parameter of cohesive laws.

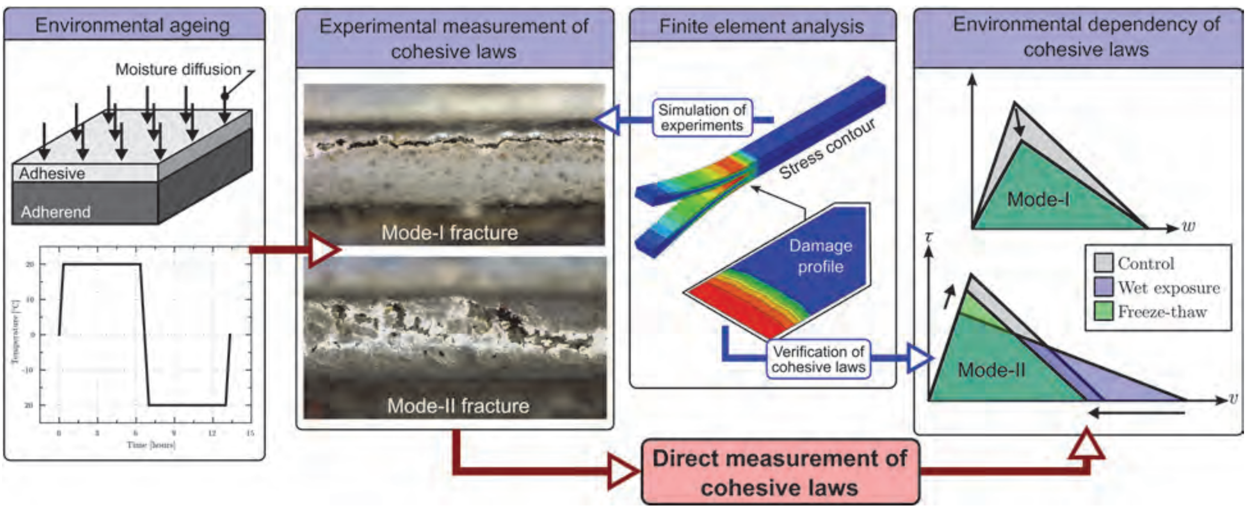

Figure 6.8 *Overview of the direct measurement method of the environmental-dependent cohesive laws*

Paper VI: "Durability of CFRP/steel joints under cyclic wet-dry and freeze-thaw condition"

This paper includes the results of extensive experimental and numerical investigations aimed at predicting the mechanical behaviour of FRP/steel joints subjected to cyclic exposure conditions. The experiments were conducted according to the future research needs identified in **Paper I**. A coupled moisture diffusion-fracture analysis model was developed (see Figure 6.9) based on the findings reported in **Paper II**, **III**, and **V**. In addition, the test results of some of the joints aged under constant exposure conditions (reported in **Paper IV**) were used in this study for the sake of comparison.

No sign of corrosion was found on the bond-line of aged DLS joints after wet-dry or freeze-thaw cycles. However, wet-dry exposure in saltwater altered the initially cohesive failure mode of DLS joints to distinct interlaminar failure mode. Freeze-thaw cycles did not negatively affect the strength of tested DLS joints, either in the presence or absence of moisture. Interestingly, it was the preconditioning in hot/wet environments that governed the lower bound of the tested joints' strength. Surprisingly, the largest strength degradations were observed for specimens dried after wet exposure. This is shown to be directly correlated with the loss of adhesive ductility upon drying, and is successfully captured by the proposed finite element analysis procedure, see Figure 6.10. The proposed modelling and characterisation scheme can reliably be used for long-term performance prediction of bonded FRP/steel joints, provided that the dependency of all the constituent materials on moisture and exposure history are obtained.

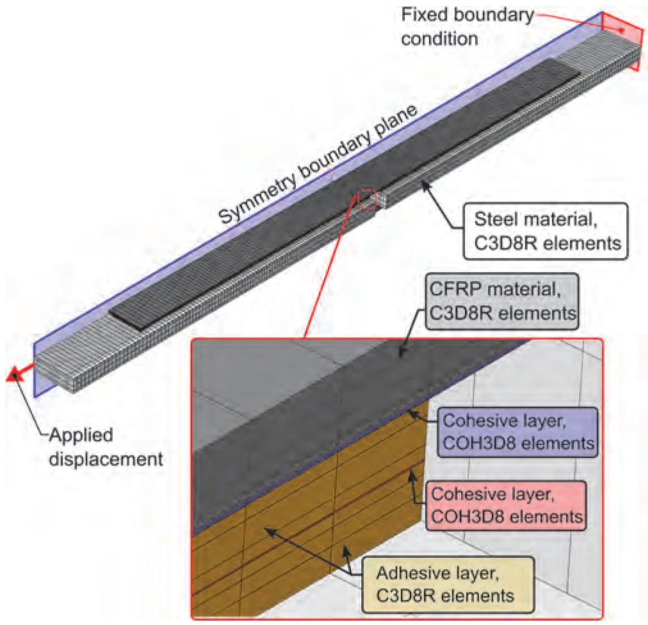

Figure 6.9 *Geometrical and mesh details of the developed predictive model*

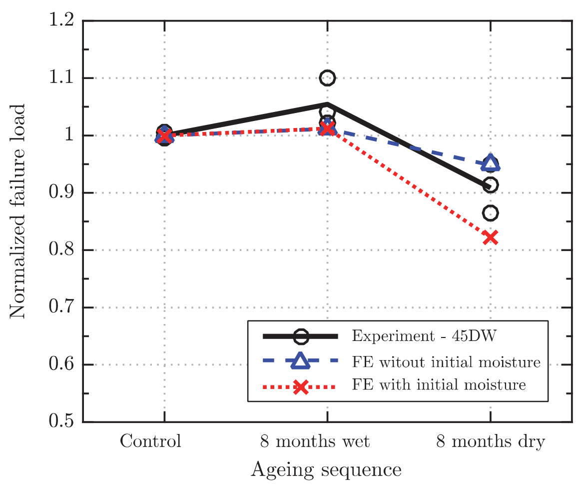

Figure 6.10 *Comparisons of FE-predicted and experimental failure load of CFRP/steel DLS specimens subjected to wet-dry exposure in distilled water at 45°C*

7 Conclusions

7.1 General conclusions

The aim of this study was to establish a framework for long-term performance and durability analysis of adhesively bonded FRP/steel joints in civil engineering applications. The state-of-the-art on durability aspects of FRP composites, epoxy adhesives and FRP/steel bonded joints in bridge applications were reviewed. From this review, hygrothermal ageing (combination of moisture and temperature) was identified as the most influential factor on long-term performance of bonded joints in steel structures. In addition, a direct correlation between moisture content and mechanical degradation was identified. The literature review provided a framework to investigate the areas that remain unclear and need further research. Subsequently, a methodology including both experimental and numerical approaches was developed.

Cohesive zone modelling (CZM) was found to be an appropriate numerical method to study the influence of various geometrical and material parameters on the long-term performance of bonded FRP/steel joints. The following conclusions can be drawn from this part of the study:

- The behaviour of FRP/steel joints with various failure modes, such as interfacial, cohesive, FRP delamination, and combined interfacial/cohesive, can be accurately predicted using the CZM. This is particularly important for durability assessments as a change of failure mode is commonly observed after environmental ageing.
- The strength of joints with cohesive failure mode and long overlaps is mainly governed by fracture energy of the adhesive material. However, the strength of joints with short bond-lines is additionally affected by the shape and maximum traction of cohesive law. As these parameters are known to be affected by environmental exposure, the results of small-scale laboratory specimens should be carefully evaluated.
- The length of fracture process zone is suggested as an appropriate parameter to consider during the design phase in order to account for the effects of environmental ageing on anchorage length.
- Information about the exposure history is essential for reliable prediction of the mechanical performance of bonded joints. For instance, considering of the presence of initial moisture content before a drying cycle is necessary to obtain a more accurate prediction.

The characterisation of the correct set of material data for durability assessments is of utmost importance. The diversity of environmental factors and possible synergy between them adds to the complexity associated with characterisation methods. The following methods are proposed:

- The material-level tests used in this study include:
  - Dynamic mechanical analysis to measure T_g of adhesive,

  - Gravimetric measurements to obtain moisture diffusion properties,
  - Tensile coupon tests to obtain environmental-dependent mechanical properties,
  - Fracture toughness tests to obtain cohesive laws.
- Given the strong dependency of mechanical properties of many polymers on moisture, it is often possible to establish relations between the mechanical property and the moisture content. These relations are particularly helpful when defining input data for numerical tools.
- The moisture diffusion properties of FRP composites may be substantially different when exposed to high relative humidity compared with immersion conditions. Therefore, care should be taken not to extend the results of one to the other.
- Open-face fracture specimens can be used in conjunction with J-integral to directly measure the exact shape of cohesive laws and their dependency on environmental exposure in relatively short periods.
- De-icing salts were generally found to be more damaging to mechanical properties and cohesive laws of the adhesive material, particularly when combined with freeze-thaw cycles. The potential formation and expansion of salt crystals is believed to be the reason for this observation.

Double lap shear specimens were used to investigate the effects of hygrothermal, wet-dry and freeze-thaw ageing conditions on mechanical performance of adhesively bonded FRP/steel joints. This configuration was mainly used due to the ease of failure detection and manufacturing, and availability in the literature. The following conclusions can be drawn:

- No sign of corrosion was found along the bond-line of aged DLS joints subjected to any of the aforementioned conditions for up to three years, suggesting a good deal of protection provided by the adhesive layer. However, the interfacial adhesion was found to weaken after extended exposure to moisture. This highlights the need to use adhesion promoters, such as silane coupling agents, even if the short-term strength of the joint is governed by cohesive failure mode.
- Short-term exposure to hygrothermal conditions may be beneficial for strength of the joints with strong adhesive/steel interfaces due to plasticization of the adhesive material and consequent peak stress reduction. However, it was observed that the presence of even small amounts of moisture at the interface of steel/adhesive for a critical time could lead to localised interfacial damage.
- The effects of the aforementioned ageing conditions on stiffness of CFRP/steel joints were found to be negligible. The often insignificant effect of these conditions on E-modulus of pultruded unidirectional composites, and slow moisture diffusion into the bond line are believed to be the reasons for this observation.
- Freeze-thaw cycles did not negatively affect the strength of tested CFRP/steel joints, either in the presence or absence of moisture. Interestingly, the preconditioning in hot/wet environments governed the lower bound of the strength of tested joints.

- The strength reductions after a complete eight-month-wet/eight-month-dry cycle in distilled- and salt-water at 45°C was 11% and 47% compared to reference CFRP/steel specimens, respectively, which are significantly larger than those observed after only the wet exposure. This observation was justified by the loss of ductility of adhesive/resin after being dried from a wet state, which gives further emphasis to the importance of exposure history.
- The mechanical performance of joints with highly permeable FRP adherends, such as the GFRP material used in this study, can be severely degraded after exposure to hygrothermal ageing conditions. Instantaneous reductions of interlaminar shear strength as well as the appearance of swelling-induced cracks in the adhesive layer of these joints are some examples of the damaging mechanisms.

A durability-predictive method based on the acquired knowledge on mechanisms of environmental damage, cohesive zone modelling, and environmental dependent material properties is presented. The method is realized using sequentially coupled finite element analysis that is found to provide reasonable predictions of the mechanical behaviour of environmentally aged joints.

7.2 Suggestions for future research

Although the present study has provided new insight into long-term performance and durability of bonded FRP/steel joints used in bridges, it has also raised new issues that should be addressed by future research. In the following, some ideas for future research are presented.

Naturally aged specimens

Long-term exposure to natural weathering conditions is very rare at material level and is not available for joints. The results of these tests, as the most realistic representative conditions, are necessary for qualitative performance evaluations of bonded FRP/steel joints. In addition, such experimental data are needed to validate accelerated testing regimes and predictive durability modelling approaches such as the one presented in this study.

Cohesive laws

On the basis of the promising application of the direct measurement method to derive environmental-dependent cohesive laws of the epoxy adhesive loaded in Mode-I and Mode-II, future research on derivation of mixed Mode cohesive laws is advised. In addition, continued research on the time-dependency of cohesive laws in the presence of moisture appears to be necessary.

Interlaminar properties of FRP composites

In this study, environmental ageing was found to degrade the interlaminar shear strength of the studied FRP materials to a great extent. Consequently, the performance of bonded joints were to a great extent governed by this material property. Therefore, further research is suggested to develop cost-efficient methods to improve durability of interlaminar properties of FRP composites. Characterisation of cohesive laws associated with delamination of FRP materials is another research topic that needs future research. The small-scale fracture process zone and unstable crack growth in laminated materials are some issues that need to be resolved [121]. The derivation of dependency of cohesive laws of FRP materials on environmental factors can be subsequently researched.

Load effects

An absolutely necessary research topic which is of high relevance to bridge applications is the characterisation of the interactions of load effects with different durations, such as self-weight and fatigue loading, and environmental ageing mechanisms on FRP/steel joints. The complicated damaging mechanisms as well as simultaneously coupled actions add to the complexity of these phenomena.

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