1 Introduction

1.1 Motivation and Background

The continuously expanding commercial air traffic of the last decades steadily increased the demands for highly efficient aircraft which allow for enhanced in-service operation times while featuring a minimum structural weight in order to reduce fuel consumption. These demands generally arise from cost aspects within a commercial sector that faces massively increased competition, as well as new requirements related to environmental aspects like sustainability and emission of exhaust and noise. In order to meet these requirements substantial effort is invested by the aircraft industry to develop improved materials and innovative design concepts for application in aeronautical fuselage or wing structures. However, the desire for minimum structural weight and extended operation times are generally conflicting design requirements which necessitate specific attention especially with respect to the fatigue and damage tolerance behaviour of these structures.

According to present airworthiness standards (FAA, 1993a,b) such airframe structures have to fulfil the requirements of the *damage tolerance* design approach, which, from a historical point of view, emerged as a supplement from the two basic design philosophies of *safe-life* and *fail-safe* (Pook, 2007). While the *safe-life* concept assumes that the structure is able to resist any load to be expected during its in-service life without exhibiting any detectable damages, the *fail-safe* philosophy assumes a redundant design which ensures safety of the whole structure even if a primary component fails (FAA, 1993b). The *damage tolerance* design philosophy generally allows for the occurrence of cracks during the in-service life, as long as it can be ensured that the damage is detected during standard inspection before reaching a critical size, as schematically illustrated in Figure 1.1(a). The design of a damage tolerant structure therefore requires a consideration and evaluation of the growth behaviour of macroscopic cracks which follow from accidental or fatigue damages. Besides experimental investigations, the evaluation of cracks and the simulation of crack growth consequently represent essential aspects for the design of airframe structures.

Up to date, the majority of conventional airframe structures still exhibit a built-up design that is composed of single, predominantly metallic, components. The resulting differential design typically consists of aluminium skin sheet panels and additional structural stiffening elements that are usually fastened to the skin sheet via rivets. For the case of a fuselage application, the stiffening elements are oriented in longitudinal and circumferential direction and act as a redundant second load path within the resultant structure, while the additional stiffness efficiently retards perpendicularly approaching cracks, as is schematically illustrated in Figure 1.1(b). In

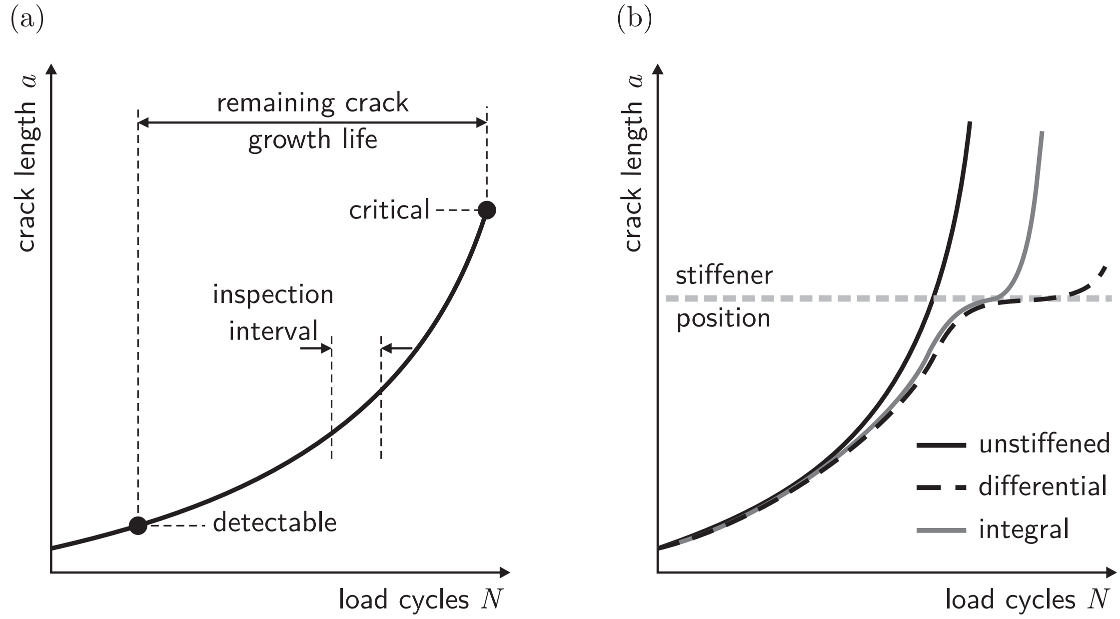

Figure 1.1: (a) illustration of damage tolerance design approach, (b) schematic comparison of different stiffening configurations

the recent past however, the usage of composite materials for primary airframe structures was continuously pushed and the percentage of composite materials within the latest commercial aircraft developments, like the Boeing 787 and the Airbus A350, has increased to fifty percent (Boeing, 2010). These trends significantly intensified the competition for metallic airframe structures and necessitated the development of innovative design concepts aiming at a combination of highly evolved aluminium alloys and innovative manufacturing techniques. This opens up potential savings with respect to manufacturing time and cost on the one hand and on the other hand offers increased freedom with regard to the structural topology facilitating an additional reduction of the structural weight. Since the typical manufacturing methods, that are applied in this context, are high speed machining processes, and joining techniques like laser beam welding and friction stir welding, the resulting structural concepts generally feature integral characteristics. As a consequence of this integral design, an alternative second load path is not available anymore which represents a significant drawback with respect to the resulting fatigue crack growth behaviour, as schematically illustrated in Figure 1.1(b). Ahead of the stiffener, the crack growth behaviour for the integral design is very similar to the differential design and the approaching crack is efficiently retarded by the additional resistance of the stiffener. However, once the crack has reached the stiffener position it also branches into the stiffener and results in accelerated crack growth again when the stiffener finally fails.

Another relevant aspect concerning fatigue life estimations of integrally stiffened structures is related to the applied manufacturing methods because the mentioned joining techniques are known to introduce a significant amount of residual stresses

into the resulting structure. Since these internal stresses can either have a beneficial or detrimental influence on the fatigue crack growth behaviour (Bussu & Irving, 2003), their consideration within the simulation methods is identified to be another important aspect. In combination with the general drawbacks concerning the fatigue crack growth behaviour, this further emphasizes the already mentioned necessity for reliable crack growth simulations of integrally stiffened structures.
Common simulation approaches for airframe structures are often restricted to pure mode I crack loading and do not consider any deflection or turning of the crack. This is usually a reasonable assumption due to the prevalent significance of mode I crack growth scenarios with regard to conservative estimations. However, crack turning and deflection can be observed quite frequently in pressurized fuselage panels (Pettit et al., 2000) and generally result in an enhancement of the fatigue life due to an additional retardation of the crack growth. The mentioned crack deflection behaviour can possibly be additionally influenced when considering non-rectangular stiffening concepts like the *isogrid* structures presented by Pettit et al. (2000). Following the experimental investigations presented by Maclin (1991), the deflected crack might even generate a flap which leads to a safe decompression of the fuselage and possibly arrests the crack (Maclin, 1991; Pettit et al., 1997).
The potential capabilities for crack retardation and crack arrest consequently motivate a more detailed consideration of crack deflection and crack turning effects. For plane problems, crack deflection is generally governed by the crack tip stress field and is usually evaluated based on the in-plane stress intensity factors or energy release rates (Erdogan & Sih, 1963; Nuismer, 1975; Richard et al., 2005). An extension of the crack turning investigations to pressurized fuselage panels involves additional effects which facilitate a possible deflection of the crack and can be considered via secondary stress intensity factors, that follow from bending (Potyondy et al., 1995), or are related to the occurrence of additional T-stresses (Pettit et al., 1997, 2000; Llopart et al., 2006).

1.2 Scope and Objective

An elaborate study on integral airframe structures was presented by Pettit et al. (2000) and Munroe et al. (2000) which included a variety of related topics, ranging from conceptual considerations of different integral designs to estimations of manufacturing costs, with a major focus on experimental testing on various scales. Even though this study also included some general aspects with regard to modelling and simulation, the presented numerical investigations were rather basic and did not include the influences of the applied manufacturing methods.
The numerical simulations in this context are performed with the finite element method (FEM) which probably represents the primary analysis method for problems in structural mechanics nowadays. However, standard finite element analyses of cracked structures typically require an explicit modelling of the crack contour with a special discretization at the crack tip positions in order to adequately rep-

resent the stress singularity at these positions. Depending on the complexity of the basic problem, the generation of an adequate FE model can therefore become a complicated and time consuming task. While this is usually acceptable for single crack evaluations, it becomes tedious and inefficient when facing a large number of crack evaluations during a crack growth simulation. When being faced with crack growth investigations of various different design configurations within a parametric study, the associated numerical effort of standard finite element analyses consequently becomes very excessive and normally does not represent a practicable solution anymore.

This issue is addressed within the present thesis and the main objective can be defined as the development and improvement of numerical simulation methods for efficient and reliable evaluation of the crack growth and the damage tolerance behaviour of integrally stiffened metallic panels for aeronautical applications. Specific tasks in this context are the correct determination of the resulting crack growth paths and the possibility to consider additional internal stresses in order to include the influence of residual stresses for the fatigue crack growth simulations.

Some of these issues were addressed by the *DaToN*[1] project, which was specifically intended to study the damage tolerance behaviour of integrally stiffened, metallic airframe structures with a special focus on the impact of residual stresses being related to the applied manufacturing techniques. The project was funded by the European Commission and parts of the present thesis are related to the work that was performed during this project. Besides a broad experimental test program (Lazzeri et al., 2011, to appear), which included fatigue crack growth investigations, as well as residual stress measurements, a specific target during the project was the development and enhancement of simulation tools with respect to an incorporation of residual stress effects in order to improve fatigue crack growth estimations of integrally stiffened airframe structures Häusler et al. (2011, to appear) and Tavares et al. (2011, to appear).

The simulation method, that is developed for this purpose, determines the stress intensity factors based on the requirement of displacement compatibility between skin sheet and stiffeners using complex stress functions. The analytical approach is limited to pure mode I crack loading and assumes a plane state of deformation which allows for an additional consideration of longitudinal bending effects. The basic idea was originally introduced for crack investigations of differentially stiffened structures (Poe, 1971b; Swift, 1979; Nishimura, 1991) and was already applied for first investigations of high speed machined panels by Fabel (2008). The implemented method within this thesis adopts certain parts of the original approaches but requires several adaptations and modifications in order to adequately account for the integral characteristics of the investigated structures. The influence of residual stresses is incorporated by a mean stress approach (Glinka, 1987; Barsoum & Barsoum, 2009),

[1]**DaToN** - Innovative Fatigue and **Da**mage **To**lerance Methods for the Application of **N**ew Structural Concepts - specific targeted research project funded by the European Commission within the 6th framework program

which is based on the superposition principle of stress intensity factors and uses a modified residual stress representation in order to determine the unknown residual stress intensity factors based on a weight function approach (Terada, 1976). The resulting (*pseudo-numerical*) simulation method allows for an automated, fast and efficient evaluation of the complete fatigue crack growth life of integrally stiffened panels under mode I loading with additional consideration of residual stress effects. The method is applied for fatigue crack growth simulations of an integrally stiffened panel that features varying residual stress fields being related to different manufacturing scenarios. The results are compared with available experimental tests from the *DaToN* project, as well as with alternative numerical solutions.

In order to account for the mentioned observations concerning crack turning and deflection, an additional simulation method is proposed in this thesis for efficient crack growth simulations under mixed mode loading conditions. The implementation was inspired by the continuous developments and the increasing popularity of enhanced numerical simulation techniques of the last years, that resulted in a variety of similar approaches which allow for a simplified representation and simulation of arbitrary discontinuities. This comprises meshless methods, like the element free Galerkin (EFG) method (Belytschko et al., 1994), as well as enhanced finite element techniques that use a locally enriched approximation on a nodal (Belytschko & Black, 1999) or element basis (Oliver, 1996). The *extended finite element method* (xFEM) probably represents the most popular approach in this context and enables a fully mesh-independent representation of arbitrary discontinuities based on a nodal enrichment (Moës et al., 1999; Dolbow, 1999). This property makes the approach very appealing for fracture mechanics because it does not necessitate an explicit discretization of the crack contour and does not require any remeshing operations when the crack propagates, which allows for fully automated finite element simulations of cracks and crack growth.

Since the extended finite element approach is not readily available within commercial finite element software codes, an independent xFEM framework is developed and implemented within this thesis that is specifically designed for two dimensional simulations of crack growth until now. The code is capable to evaluate the in-plane stress intensity factors using the interaction integral technique (Yau et al., 1980) and thus allows for a consideration of crack turning effects under mixed mode loading and a simulation of crack growth based on the maximum tangential stress criterion (Erdogan & Sih, 1963).

In addition to this common two step approach, an alternative procedure is introduced which combines the advantages of the extended finite element method with the capabilities of the *material force* concept for a one step evaluation of crack state and crack growth direction. The material force is based on the energy-momentum tensor (Eshelby, 1975) and acts as an internal force Maugin (1995) that follows from a configurational stress equilibrium and can be used for evaluation of crack state and crack deflection (Steinmann, 2001; Mueller et al., 2002; Denzer et al., 2003).

The proposed combination of both concepts is validated and the capability of the new simulation method is investigated based on several crack growth scenarios under mixed mode loading. The method is then applied for crack growth simulations of varying stiffened panel configurations in order to study the influences of different stiffener properties and additional internal stresses on the crack deflection and crack turning behaviour with regard to airframe applications. Due to the current limitation of the xFEM to plane problems, the simulations in this context do not consider out-of-plane deformations or bending effects and use a simplified stiffener representation.

1.3 Layout

Chapter 2 reviews the continuum mechanical setting and discusses relevant aspects of the linear elastic fracture mechanics theory. This includes complex stress functions, energy integral formulations and the material force concept, as wells as aspects concerning fatigue crack growth and crack deflection.

Chapter 3 presents the basic principles of the standard finite element method within the context of fracture mechanics and introduces the general concept and some major theoretical aspects of the extended finite element method.

Chapter 4 describes the major implementation aspects of the xFEM and introduces the proposed combination with the material force concept. This is followed by a basic validation of the new approach and automated crack growth simulations for a variety of different scenarios under mixed mode loading.

Chapter 5 reviews relevant residual stress basics with focus on thermal residual stresses following from welding manufacturing and their influence on cracks and fatigue crack growth.

Chapter 6 presents the required expressions for the implemented pseudo-numerical simulation approach including all applied adaptations, a basic model validation and the developed residual stress module.

Chapter 7 applies the implemented pseudo-numerical simulation approach for fatigue crack growth investigations of a two-stiffener panel with special focus on the influences of different manufacturing techniques, including a comparison with experimental results and alternative numerical solutions.

Chapter 8 extends the numerical investigations to mixed mode crack growth simulations of stiffened panels based on the presented xFEM in order to study the effects of different stiffening configurations on crack turning and deflection, with specific focus on the influences of additional internal stresses.

Chapter 9 concludes the thesis with a summary of the performed work and the principal results, including some suggestions for possible fields of further research.