1. INTRODUCTION

1.1 MOTIVATIONS

The research conducted in the field of fatigue during last 20-30 years can essentially be divided into two categories: fundamental research conducted in order to understand the mechanisms of fatigue phenomenon and *applied research*, which is focused on the development of tools needed solve practical fatigue problems. Applied research can also be divided into two categories: research conducted to develop *fatigue design* rules for new structures, and research related to *fatigue evaluation* of existing structures.

Applied research in fatigue design has resulted in what is known as the nominal-stress or *S-N* curve fatigue design concept [1.1], [1.2], [1.3]. In the nominal stress approach, *S-N* curves are developed by statistical analysis of constant-amplitude full-scale fatigue test data (Figure 1.1). The *S-N* curves based approach leads to adequate fatigue design of structures loaded by constant-amplitude as well as by variable-amplitude fatigue loads. Generally, little or no fatigue problems develop if *fatigue design* of new structures is made according to existing fatigue codes and recommendations.

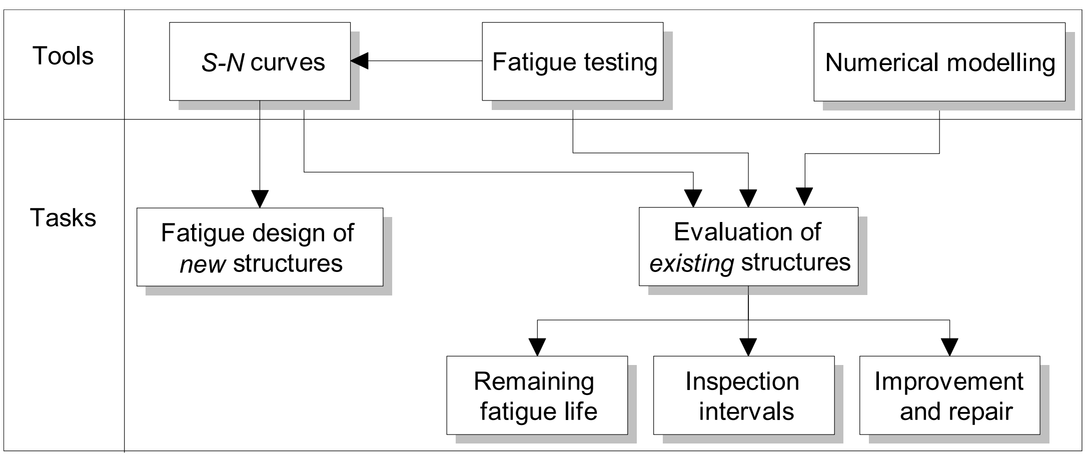

Figure 1.1 : *Tools and tasks of fatigue analysis.*

Fatigue evaluation of existing structures involves estimating the remaining fatigue life, determination of required inspection intervals, and the study of improvement and repair methods [1.4]. Fatigue evaluation of existing bridges is necessary due to increases in the load intensity of railway and road traffic [1.5]. Fatigue evaluations are also needed in order to determine if old structures must be replaced or strengthened. In many cases, it is more economical to evaluate and subsequently reinforce an existing structure, than it is to erect a new one [1.6], [1.7]. Thus, accurate fatigue evaluation procedures are essential to conduct a condition evaluation of existing structures.

There are three principal methods available to carry out fatigue evaluation of existing structures (Figure 1.1). Each has its advantages and disadvantages. The nominal-stress (*S-N curves*) method is simple, but typically leads to very conservative evaluation results. *Fatigue testing* of existing structures (or structural details [1.8], [1.9]) generally leads to a rather precise fatigue evaluation, but is expensive and time consuming. *Numerical modeling* techniques [1.10], [1.11] are inexpensive and rapid compared to fatigue testing, but numerical models need calibration. This study will be concentrated on numerical modeling. It is believed that a reasonable fatigue evaluation model can be developed. However, prior to developing a new fatigue evaluation model, the disadvantages of existing evaluation models will be discussed.

Before the disadvantage of existing models can be analyzed, three criteria of a target model will be established (Figure 1.2) :

– Fatigue life is influenced by five groups of influence factors : loading, geometry, material, environmental parameters, and fabrication-induced residual stresses. Each group contains a number of sub-parameters. For example, some of the sub-parameters of loading are the nominal stress range, the mean stress, the load sequence, etc. Thus, the *first* criterion of a target model is that it should take into account a possibly large amount of influence factors.
– During fatigue crack propagation, the effects of the influence factors interact. Fatigue crack propagation depends on the values of the influence factors (which can vary in time), and relations between them. Changes in one parameter can radically change the way a fatigue crack propagates : crack propagation can accelerate, slow down, arrest, or continue until fracture of the cracked section occurs. Therefore, the *second* criterion of a target model is that it should be able to simulate all important aspects of fatigue crack propagation.
– Fatigue crack propagation involves three crack propagation stages. However, only two stages essentially contribute to the fatigue life (see Chapter 2). These two stages are the portions consisting of crack initiation and stable crack growth. Thus, the *third* criterion of a target model is that it should be able to simulate both the crack initiation stage and the stable crack growth stage.

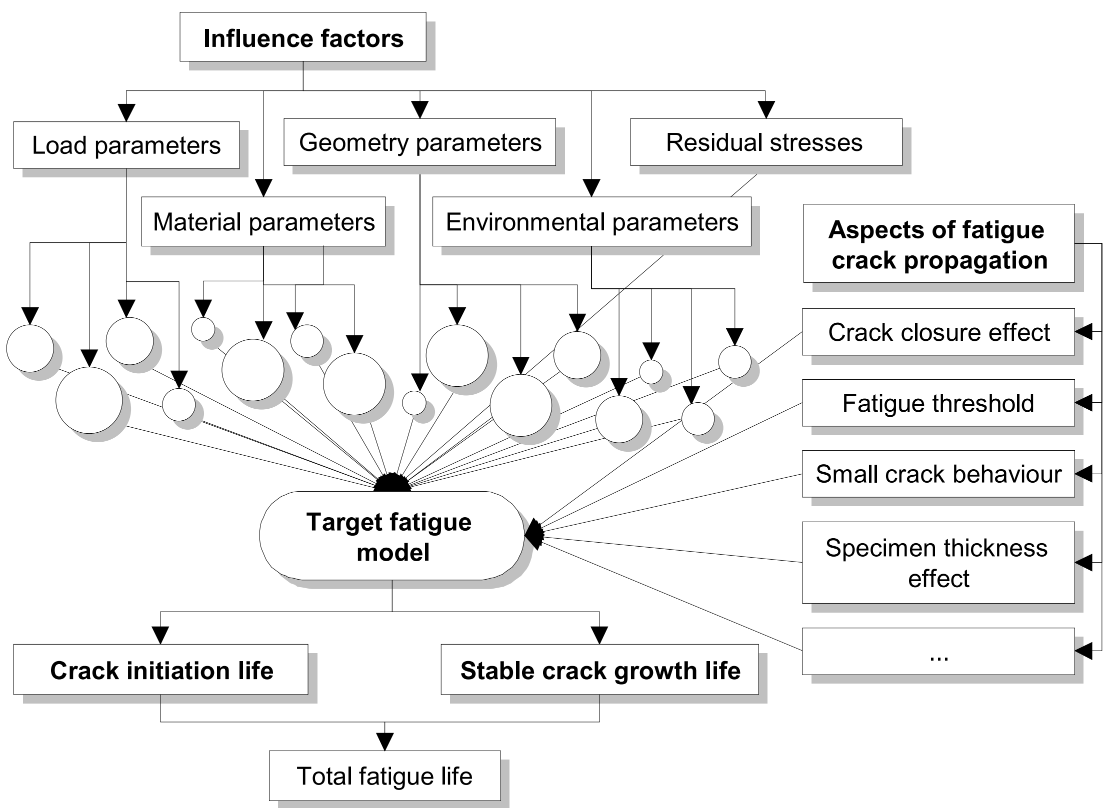

Figure 1.2 : *The parameters to be taken into account by a target fatigue model.*

Two groups of existing fatigue models are compared to a target model in this section. The first comparison includes a fracture mechanics based crack propagation models, where the model developed by Wang and Blom [1.12] is taken as an example. This model takes into account all important loading parameters. In addition, it is capable of simulating several important aspects of fatigue crack propagation such as crack-closure effect, fatigue threshold, small crack behavior, and crack behavior under cyclic compression. The influence of detail geometry is also accurately considered by the model of Wang and Blom. However, the model can not account for the effects of material and environmental parameters. And most importantly, the model under consideration can only simulate stable crack growth life and does not include features to calculate the crack initiation life. Nevertheless, the model of Wang and Blom can be considered as one of the best fatigue models available.

The second group of models are based on the local strain approach [1.13], [1.14], [1.15]. This approach utilizes a strain-life relationship developed from the work of Basquin [1.16], Coffin [1.17], Manson [1.18] and Morrow [1.19]. Models based on the local strain approach are able to take into account a number of load, geometry, material and environmental parameters. The primary disadvantage of these models is an inability to simulate the stable crack growth life.

It can be summarized that fracture mechanics models are capable of simulating stable crack growth life, but do not allow evaluation of the crack initiation life. Therefore, these models are well suited to simulate the fatigue behavior of details with severe notch conditions such as welded structures. The local strain approach based models on the other hand, can simulate the crack initiation life, but are not applicable to calculation of the stable crack growth stage. This implies that these models are well suited to simulate fatigue behavior of details with long crack initiation life such as details with smooth notches and holes, as compared to the stable crack growth life. However, there are details with comparable crack initiation and stable crack growth life (e.g., improved welds, sharp notches etc.). Simulation of the fatigue behavior of these details using existing fatigue models is conservative. This is because the both groups of models discussed above do not consider or ignore a portion of the actual fatigue life. For example, in the fracture mechanics fatigue models, the crack initiation life is not considered. Similarly, in the local strain approach based models, the stable crack growth life is not taken into account. Currently, no models exist which posses the capability to simulate both crack initiation and stable crack growth portions of fatigue life.

It can be concluded that available fatigue models do not fulfill the above established criteria. There is no model available which can take into account the influence of all important fatigue parameters, simulate various aspects of fatigue crack propagation, and consider both propagation stages (i.e., crack initiation and stable crack growth). Therefore, a new fatigue model should be created - a model which corresponds more to the target models than to existing model. In addition, a new model must be analyzed and the possibilities of its application shown.

1.2 GOALS

Based on the above discussion, it is clear a new fatigue model is needed. The requirements of a target fatigue model can be used to establish the goals of this study. The goals are:

1. Creation of a new ***fatigue model*** that can account for a large number of parameters which influence fatigue behavior and consider a large range of fatigue aspects.
2. Application of the new model to ***classification of fatigue parameters*** according to their influence on fatigue behavior.
3. ***Analysis, simplification and application of the model*** including :
   - verification and parametric study of the model,
   - development of a new equation for the crack propagation rate,
   - creation of a simplified fatigue model,
   - presentation of application examples of the model.

1.3 SCOPE

The following *influence factors* of fatigue behavior will be included :
1. fatigue loading of any type,
2. any form of detail geometry,
3. ductile materials such as structural steel and aluminum alloys,
4. all possible distributions of fabrication-introduced residual stress.

The effects of environmental parameters is excluded from the scope of this study.

The following aspects of fatigue crack propagation will be considered in the model :
1. fatigue threshold,
2. crack-closure effect,
3. effects of variable-amplitude loading on fatigue behavior,
4. small crack behavior,
5. specimen thickness effect,
6. crack behavior under cyclic compression.

As previously mentioned, there are three distinct stages of crack propagation. However, only two of them will be considered and are listed below :
1. Crack initiation (CI) stage.
2. Stable crack growth (SCG) stage.

The third stage, unstable crack growth, is short compared to first two stages and is not considered.

1.4 ORGANISATION OF THE THESIS

The organization of this thesis is shown in Figure 1.3, and illustrates the relationships between topics and their grouping into chapters. The thesis begins with an *introduction* where the scope, motivation and goals of the thesis are discussed. The introduction is followed by a study of the theoretical background - *theoretical study* which presents the basic concepts that will be used in later chapters. It includes a review of the stress concentrators (crack initiators and fatigue cracks), gives an overview of fatigue crack propagation and includes selected topics such as crack closure effect, small crack behavior, etc., and introduces three fatigue life prediction methods (*S-N* curve approach, local-strain approach and fracture-mechanics approach). At the end of the theoretical study, the equations of Dugdale crack opening displacement are generalized.

Fatigue crack propagation modeling is the focus of the study and the new contribution to the scientific discussion about fatigue. Modeling is made in five parts. Firstly, representation of crack propagation path by uni-dimensional elements is introduced, and numbering and size requirements of elements, given. Secondly, a method to calculate fatigue life of elements is presented. Thirdly, various aspects of modeling such as simultaneous damaging of elements and differentiation between crack initiation and the stable crack growth stages are discussed. Fourthly, a crack closure model based on dynamic behavior of a Dugdale crack model is developed. And fifthly, the overall algorithm of the model is explained.

A *verification of the model* is carried out in order to see whether simulated results correspond to fatigue test results. Verification includes two groups of comparisons : quantitative and qualitative. The quantitative comparisons are carried out by comparing the simulated fatigue data to the fatigue test results and to the results of finite element modeling. The qualitative comparisons consist of collating the *shapes* of crack propagation curves, simulated under various loading conditions, to equivalent measured curves. A verification of the model is succeeded by the *parametric study* which is conducted to determine the influence of the input parameters on the results of the crack propagation simulations. Four sets of parameters are studied: numerical, material, geometrical and load parameters. All the studied parameters are classified by their influence on the fatigue life. Based on the verification and the parametric study of the model, the application limits of the model are established.

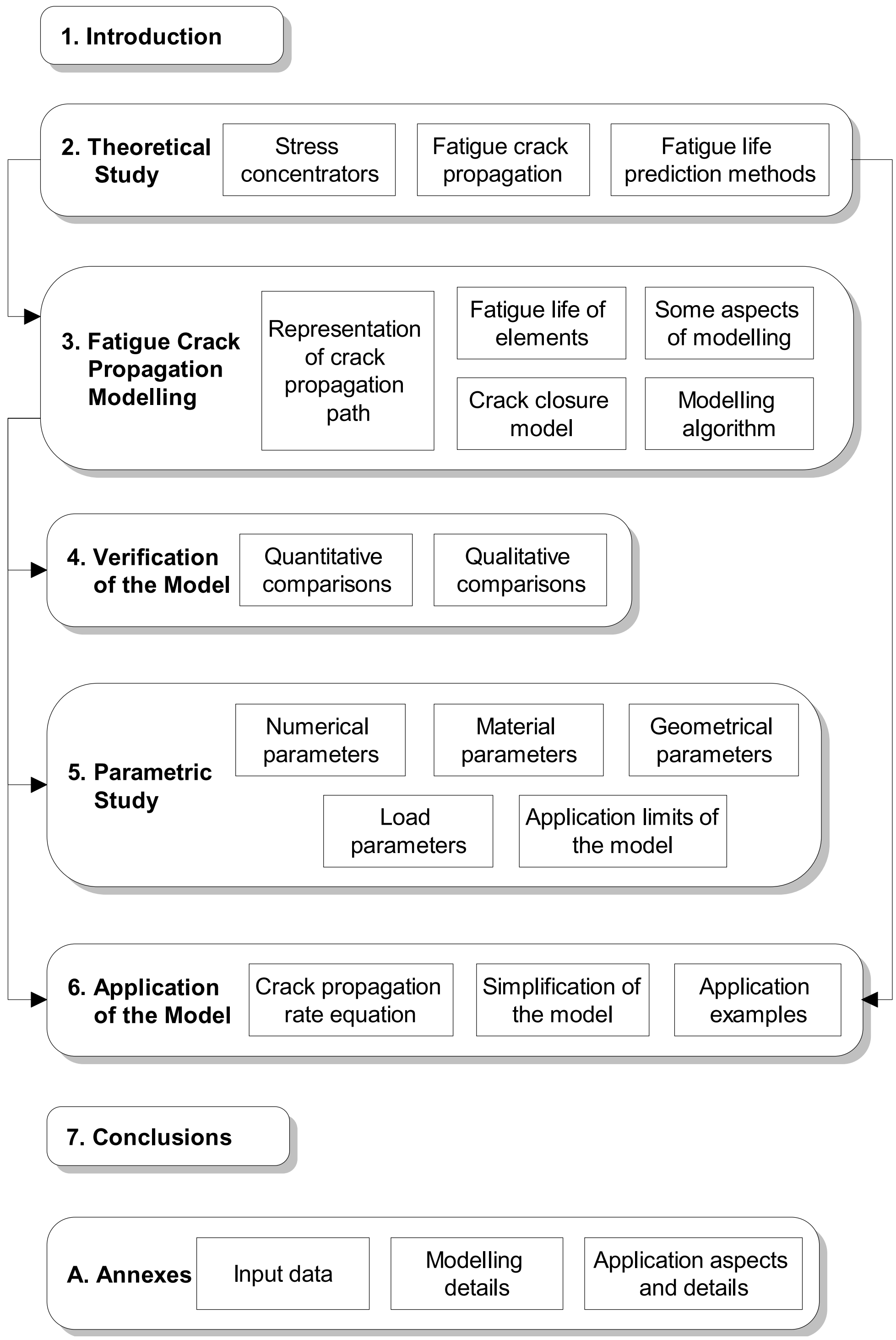

Figure 1.3 : *Organization of the thesis.*

An *application* of the results of this study is made in three parts. Firstly, a crack propagation rate equation, different from the Paris equation, is developed on the basis of modeling principles of this study. Secondly, a simplified crack propagation model is developed based on a proposed crack propagation rate equation. Thirdly, two examples are given, one concerning the comparison of fatigue properties of structural steels, and the other - the comparison of the model to method based on *S-N* curves. The thesis finishes in Chapter 7 with an overview of the proposed methodology followed by review of original aspects of the thesis. Results of the study as well as proposals for further work are also presented. The annexes given after Chapter 7, contain information regarding the input data of the model and various details and aspects of modeling.