LIFE ASSESSMENT AND DAMAGE TOLERANCE OF WIND TURBINES

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ABSTRACT

A survey of the safe and durable operation of fatigue critical structures in wind turbines has been attempted, including safe life assessment and possible application of damage tolerance principles. A research programme to assist safe and durable operation of wind turbine rotors in the Netherlands is reviewed.

KEYWORDS

Wind turbines; fatigue; steels; composites; safety; damage tolerance.

INTRODUCTION

Wind turbines pose a unique combination of problems for their successful design and operation:

- service lives with very large numbers of load cycles
- complex dynamic load histories
- widely varying environmental conditions
- low allowable prime cost
- minimal maintenance
- no well-founded codes and regulations.

These problems are linked by a common factor, structural and material fatigue. Fatigue is a primary cause of wind turbine failures, notably in the rotor blade/ shaft assembly, and has major implications for the design and operational requirements of safety and durability.

FATIGUE DAMAGE IN ENGINEERING STRUCTURES

Fatigue damage in engineering structures is a time-dependent process that may be generally described as shown in Fig. 1. There are three time periods:

(1) An initial period in which design and/or material deficiencies causing premature (unanticipated) fatigue cracking are eliminated by modifications or redesigns.

(2) A period in which fatigue cracking is essentially random and the damage rate, i.e. the number of cracks with time, is low.
(3) A final "wear-out" period in which the fatigue damage rate increases.

Provided the damage rates in the earlier periods correspond to acceptably low probabilities of structural failure (as, of course, they should) then the final period is all-important for continued safe and economic operation. This is illustrated in Fig. 1 by the significantly different service lives that may be obtained depending on the fatigue design philosophy, safe-life or damage tolerance, discussed in the next section.

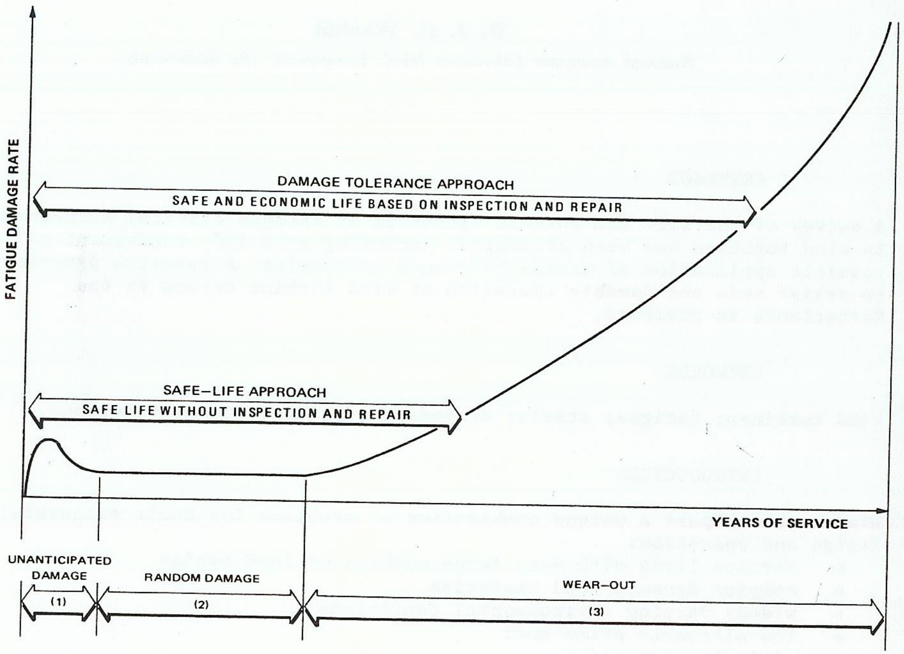

Fig. 1 Schematic of fatigue in engineering structures

PRINCIPLES OF SAFETY AND DURABILITY IN DESIGNING AGAINST FATIGUE

Structural Fatigue Design Philosophies

There are two basic philosophies of structural fatigue design:

- the SAFE-LIFE approach
- the DAMAGE TOLERANCE approach.

The safe-life approach means to design for a finite life during which significant damage (i.e. cracking and/or failure) will not occur. It is

particularly relevant to structures that are difficult to inspect for damage.

The damage tolerance approach requires designing for an adequate service life without significant damage but also enabling operation beyond the actual life at which such damage occurs. Operation is thus permitted when the structure is cracked - as might occur prematurely - but it must be shown that the damage will be detected by regular inspection before it grows to the extent that residual strength falls below a safe level. This approach is particularly relevant to structures that remain safe even when easily inspectable damage is present, e.g. a multiple load path structure that tolerates failure of one or more load paths.

Definitions of Safety and Durability

So far, safety has been mentioned without qualification. However, in practice the SAFETY REQUIREMENT is a balance of design, operational and economic factors such that the probability of failure during the design life is less than a value deemed to be an acceptable risk.

Since all structures deteriorate in service, e.g. Fig. 1, the probability of failure increases with time. There is thus a SAFETY LIMIT, which may be defined as the time beyond which the risk of failure is considered to be unacceptable unless preventative actions are taken. For safe-life structures the necessary preventative action is retirement from service. But for damage tolerant structures immediate retirement is not the only option. In the first instance preventative action is repeated inspection, followed by repair if it is required and if it is feasible. Only when repair is not feasible or when the frequency of inspection and repair becomes uneconomic need the structure be withdrawn from service.

Consideration of preventative action for ensuring safety leads to the DURABILITY REQUIREMENT. The necessity for a structure to be durable means primarily that the economic life, including any inspections and repairs, should equal or exceed the design life.

SAFETY AND DURABILITY OF WIND TURBINES: AN OVERVIEW

As mentioned earlier, fatigue is a primary cause of wind turbine failures. Safety and durability are achievable only by ensuring sufficient reliability against fatigue failure, including the possibility of accidental damage (a random event) occurring to fatigue damaged structure.

At present the information required for safety and durability of fatigue critical wind turbine structures is either not available or very limited, Table 1. However, this has not hindered the design, manufacture and operation of many kinds of medium-to-large wind turbines, whose rotor assemblies generally are lightweight (to be cost effective) and are therefore most probably fatigue critical. This far from ideal situation has come about, at least in part, because of the lack of well-founded codes and regulations.

Besides indicating a dearth of much essential information, Table 1 also shows that the damage tolerance approach necessitates a considerably broader data base than the safe-life approach. Because of this, and despite the possibility in some cases of designing easily inspectable multiple load path structures, it is currently unrealistic to expect or require priority to be given to the damage tolerance approach for designing fatigue critical wind turbine structures. Safe-life design (whether well-founded or not) is likely to predominate for the foreseeable future.

TABLE 1 Information Required for Safety and Durability of Fatigue Critical Wind Turbine Structures

DATA ITEMS	DESIGN AND OPERATIONAL APPROACH: SAFE-LIFE	DESIGN AND OPERATIONAL APPROACH: DAMAGE TOLERANCE	REMARKS
• long life (>10^8 cycles) constant amplitude fatigue data for materials and joints	●	●	• some data available for steels and steel welds • no data for bolted steel joints, composites, and composite and metal/composite joints
• actual dynamic load history measurements for generating reference spectra	●	●	• becoming available: however, load histories are complex
• representative spectrum fatigue data for materials and joints	●	●	• not available
• environmental effects on fatigue and residual strength of materials and joints	●	●	• some data available for steels, steel welds, glass and carbon fibre composites • no data for bolted steel joints, wood, composite and metal/composite joints
• factors of safety for safe-life structures	●		• informed guesses available for steels only
• development of fatigue damage: correlation of experiments with prediction using cumulative damage models, especially for spectrum loading		●	• currently possible only for metals: specimen and crack geometries must be fairly straightforward: environmental effects not included • damage models for composites not yet available
• analysis of residual strength in the presence of detectable damage		●	• currently possible only for metals: specimen and crack geometries must be fairly straightforward
• choice of inspection methods and determination of inspection intervals (includes possible factors of safety)		●	• safety must be ensured by economically feasible inspections: this is a complex problem about which virtually nothing is known for wind turbines
• methods of maintenance and repair		●	• some information available for weld repairs and metal or composite patching of damaged metal and composite structures (aerospace)

On the other hand, in the absence of failures or obvious damage there will be great reluctance to retire safe-life designed structures when the design life has been reached. Undoubtedly it will be argued that the life should be extended either because the original design assumptions were excessively conservative or because it should be possible to guarantee continued safe and economic operation by inspection and eventual repair, i.e. by a delayed application of damage tolerance principles.

From the preceding discussion it follows that much additional information concerning both safe-life and damage tolerance aspects is required in order to guarantee safe and durable fatigue critical wind turbine structures. In particular, there is an urgent need for research programmes that will assist (a) certificating authorities in drawing up codes and regulations and (b) manufacturers in developing methods of complying with them.

EXAMPLE OF A RESEARCH PROGRAMME FOR FATIGUE CRITICAL WIND TURBINE STRUCTURES

Previous sections discussed fatigue critical wind turbine structures in general terms. It is possible to continue this discussion further, but it is more illustrative here to describe an actual research programme. The Netherlands Energy Research Foundation (ECN) and the NLR are conducting a short term programme to quickly provide information to assist safe and durable operation of 25-35m diameter rotors in the Netherlands. The emphasis is on safe life assessment. However, damage tolerance aspects are also being considered.

The programme is outlined in Table 2. There are three parts:

(1) Part I includes a literature study of high-cycle fatigue of low carbon steels and composites, especially concerning the failure modes of composite joints and the effects of variable amplitude loading on the fatigue limits of steels. Basic fatigue life curves to large numbers of load cycles will be obtained for unidirectional glass fibre composites with and without moisture preconditioning. Some notched and unnotched steel coupons will be tested to check existing fatigue life curves, notably in the long life regime (>10^8 cycles). Reduction factors to account for scatter and environmental influences will be determined.

(2) Part II requires an inventory and selection of joints involving steel welds, glass fibre composite/composite and steel/glass fibre composite. Fatigue life data will be obtained for the selected joints, including failure modes and inspectability for damage before failure. Relations between fatigue life curve shape, type of joint and failure mode will be determined.

(3) Part III requires generation of a reference load spectrum and history, preferably based on measurements on different types of rotor in several countries. The reference load history will be used to conduct spectrum fatigue life tests on the same types of specimens as in Parts I and II. As before, the failure modes of joints and their inspectability for damage before failure will be determined.

TABLE 2 Outline of a Short Term Research Programme for 25-35m Diameter Rotors of Wind Turbines on a Coastal Test Site in the Netherlands

PROGRAMME PARTS	CALENDAR YEARS 1	2	3
I: ACQUISITION OF BASIC DATA			
• literature study	■		
• manufacture of coupon specimens	■		
• constant amplitude fatigue tests*: S-N curves for steel	■		
• constant amplitude fatigue tests*: P,ε -N curves for composites	■	■	
II: EVALUATION OF JOINTS			
• selection of types of joint	■		
• manufacture of joint specimens	■	■	
• constant amplitude fatigue tests*: S-N curves for steel welds		■	
• constant amplitude fatigue tests*: P,ε -N curves for composite/composite		■	
• constant amplitude fatigue tests*: P-N curves for steel/composite		■	
III: VARIABLE AMPLITUDE FATIGUE			
• development of a reference load spectrum and history	■	■	
• manufacture of coupon specimens		■	
• selection and manufacture of joint specimens		■	
• spectrum fatigue of steel and composite coupons		■	■
• spectrum fatigue of joints			■

* S = stress; P = load; ε = strain

The results will be used for safe life assessment of wind turbine rotor joints according to the methodology shown in Fig. 2. Note that it is assumed that damage rules can be derived for calculating spectrum fatigue lives from constant amplitude data. It may be difficult to obtain satisfactory rules for some types of joint: the remedy is to rely on more extensive spectrum fatigue testing. Also note that additional spectrum fatigue testing is indicated if the actual or assumed load histories are not similar to the reference load history and if the joints are not similar to those in the programme.

Safe life assessment for concept joints leads to straightforward conclusions. Either the estimated lives are adequate and the concepts become definitive, possibly with some refinement if the joints are clearly overdimensioned, or else the joints must be redesigned.

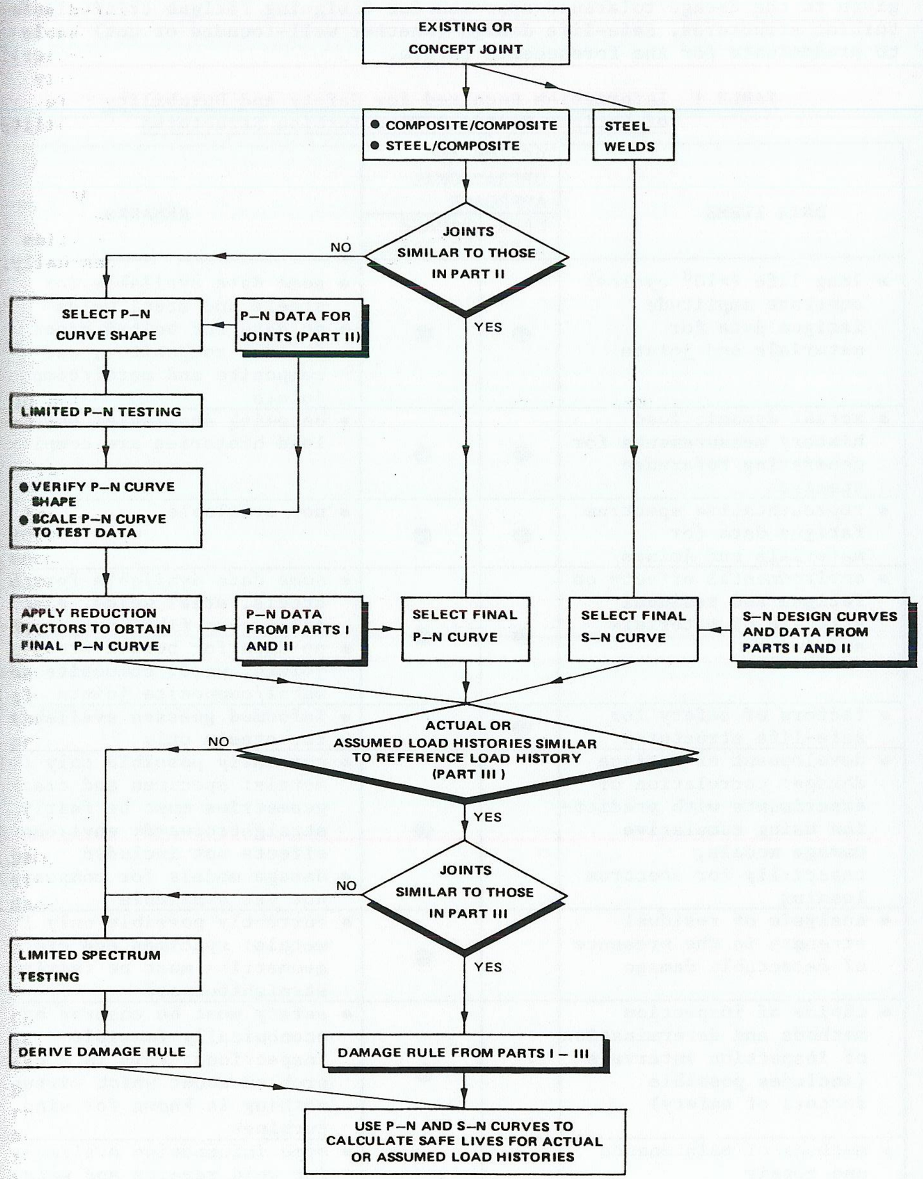

Fig. 2 Methodology of safe life assessment for wind turbine rotor joints

For existing joints the situation is more complicated. If the estimated safe lives are adequate no immediate action need be taken (but note the probable pressure to continue operation beyond the design life, as mentioned earlier). If the estimated lives are inadequate there are the possibilities of early replacement by redesigns, ad hoc modifications, and institution of a life extension programme using damage tolerance principles. The latter possibility is likely to be favoured, at least in the first instance.

In any event, the determination of failure modes and inspectability for damage before failure of the joints tested in Parts II and III of the programme will provide a basis for further exploration of the possibilities of using damage tolerance principles to extend service lives and, eventually, to design for damage tolerance.

SUMMARY

In this paper I have attempted a survey of the safe and durable operation of fatigue critical structures in wind turbines, paying particular attention to rotors. The purpose is to stimulate discussion of the various aspects involved and the best ways in which safety and durability can be achieved.

This effort was possible only by drawing on the considerable experience and background information provided by colleagues from the ECN and NLR.