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Fatigue of selected GRP composite components and joints with damage evaluation

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ABSTRACT

The paper summarises the most important results of selected experimental programmes on static and fatigue strength of heavy loaded components and joints made of glass reinforced plastic (GRP) composites, having been recently performed in fatigue laboratory of the SVÚM a.s. research and testing institute. Components like GRP trailer leaf springs, springs for railway freight vehicles are addressed, along with heavy loaded joints like stud connections in rotor blade roots at different loading and environmental conditions. It was confirmed during the different kind of tests that fatigue damage accumulation can be well monitored particularly when there are no defects or imperfections in the material. Then the damage curve usually had the typical three-stages sigmoidal shape. In case of fatigue tests of stud joints, where damage was located into the bonded area inside the specimen, temperature changes were considerably more sensitive than displacement and detailed temperature monitoring indicated weak areas in the full scale model specimens. Sudden break was mostly characteristic for defect material with insufficient wet out or with different bubbles and voids. After a more detailed analysis of fatigue tests, some further links like connections between total fatigue life and initial stiffness or initial temperature increase gradient were indicated.

1. Introduction

Glass fibre reinforced plastics (GRP) have been used as structural materials already for more than 50 years [1,2]. In the beginning of their applications, very little was known about fatigue and damage mechanisms of GRP materials. It was hoped that fatigue resistance would be at least as good as those of metals. The propagation of microcracks in the matrix was expected to stop at the fibres. Since then composite materials have successfully been applied in many other areas of engineering and industry, not only in gliders and aircrafts, where they allowed tremendous improvements in structures. On the other hand, penetration of GRP to other industries than aircrafts or wind turbines has been pursued quite slowly, rather due to conservatism of many designers, who have not been familiar with numerous characteristic differences in comparison with steels, than due to unsuitable properties of the materials themselves. Another problem of wide application of polymer composites in heavy loaded structures, like e.g. transport vehicles is that even quite well-know techniques as global–local approaches, which can be used for designing with good results, are not yet usually implemented in commercial codes [3].

One of the most important differences between GRP and metals is fatigue damage process. In metals, fatigue loading usually results in forming areas of repeated plastic deformation, usually very local – formation of persistent slip bands. Initiation of small fatigue microcracks is the next stage, followed by formation of main crack growing more or less rapidly to final failure. In case of high cycle fatigue, the damage is always very localised and no changes of global component properties can be usually observed, just sudden final break. On the contrary, fatigue damage process in GRP materials is mostly continual and global in the volume. Resin cracking followed by gradual damage of interfaces between fibres and resin is a continuous process being developed during the whole fatigue life and resulting in three typical fatigue damage phases: (i) initial stiffness drop-off, (ii) more or less long phase of linear changes and (iii) rapid stiffness reduction before final failure [4–6].

Numerous works have been recently carried out with the aim to characterise the fatigue damage process in different long fibre composites at different loading conditions and describe it using specially developed models [7–9]. Some of the models have been quite recent, like the model presented in [10] describing the fatigue damage process in terms of stiffness degradation. The model is based on specific material parameters and is applicable even for variable loading. The fact that stiffness degradation is a general characteristics, which can be caused by different damage mechanisms, is discussed in [11] and theoretical models are provided. Other works are aimed at specification of different damage mech-

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anisms connected with different load amplitudes including overloading cycles and confirm that a simple application of Palgrem–Miner's rule of damage cumulation is impossible due to very different damage mechanisms at different loads [12].

In some cases, particularly when microstructure imperfections in the material occur, which is quite frequent case, the three phases can be depressed and the component breaks suddenly like a metal one. Such issues are discussed in the paper using selected examples of fatigue tests of heavy loaded GRP components and glued joints. An attention is addressed to different laboratory methods of damage accumulation monitoring and their comparison.

When a manufacturer intend to introduce a new component or structure into the market, such the component usually has to be certified. Particularly sufficient durability, safety and reliability are the major issues during certification processes, the strictness of which depends on the field of the component application and on the fact, whether a possible failure of the component can result in casualties and economic waste. Static strength and fatigue durability are usually the major properties which have to be demonstrated for the certification process. Full-scale tests or test of full-scale models of subcomponents usually are the most important way to demonstrate adequate and requested properties.

Strength and fatigue tests can be generally performed by two ways:

– as simple certifications tests, when just limit static strength or number of fatigue cycles at a given, requested load or stress amplitude is being evaluated and reported or
– as more comprehensive and sophisticated tests, more exactly research experiments, during which as much as possible experimental information is being evaluated and recorded.

Unlike the former case, very important information and knowledge on damage mechanisms can be obtained in the latter case. The damage accumulation measurement can be performed using a number of different non-destructive techniques including replication, light and electron microscopy, X-ray radiography, ultrasonics, stiffness change, and thermography [13]. More recently, several works have been published, where damage accumulation in composites have been studied using sophisticated, labour and time consuming methods, like sectioning of specimens with optical microscopy, acid digestion of resin combined with fibre lengths counting [14]. Some new approaches concerning special applications have been described in recent literature, e.g. non-destructive ultrasonic tests using circumferential plate waves in GFRP-tube-like components [15]. Other works describe results of use of acoustic emission, which are interpreted as encouraging, being very well correlated with stiffness changes and microstructural observations [16]. Acoustic emission also can be considered as the main damage monitoring method providing a useful information on current material's damage state and being a useful damage parameter and damage criterion for fatigue life predictions [17,18]. However, other works point out that it is necessary to understand, how different damage mechanisms occurring in composites contribute to the overall acoustic emission signal [19].

Showing a significance of damage accumulation research during static and fatigue testing of the selected components and evaluation of links between static strength, fatigue life and limit states is one of the aim of this contribution, which comprises the most important results and analyses of four experimental programmes, namely (i) static pull-out and fatigue tests of full-scale experimental model test pieces of joints between studs and GRP of a wind turbine rotor blade, (ii) full-scale static and fatigue tests of studs glued into a wood epoxy wind turbine rotor blade root at room temperature and −40 °C, (iii) fatigue tests of GRP trailer leaf springs and (iv) fatigue tests of railway freight vehicle leaf springs.

2. Joints of studs and GRP in wind turbine blades

Joining of two essentially different types of materials is a potential source of technical problems. A perfect solution to such the problem is expected particularly in heavy loaded structures and particularly in case of fatigue loading. Not only bonding itself and optimization of adhesives has to be considered, but also possible consequences of different physical properties of the two materials, like e.g. E-modulus, even if strength of the materials is similar at all.

Roots of rotor blades are considerably loaded parts of wind turbines with a complicated, complex service loading. The blades are usually connected to the rotor hub using steel studs attached in holes with a suitable adhesive. Besides blades themselves, stud connections belong to components affecting reliability and safety of wind turbines operation very significantly. Therefore, experimental testing of static strength of studs and their fatigue life, performed on full scale models to verify designed mechanical properties are of a great importance.

Schematic view of a full scale model of the stud joints is in Fig. 1. On the basis of calculations and experimental results and analyses of preliminary static and fatigue tests, it was eventually decided to perform quite detailed experimental monitoring of damage accumulation.

In case of *static tests*, the measurement of continuous damage was performed using six longitudinal strain gauges glued on the specimen surface, on both sides with positions (i) near stud mouth, (ii) near stud end and (iii) in the specimen centre. Damage accumulation during fatigue loading was eventually monitored using numerous thermocouples attached to the specimen surface at distances according to Fig. 2. Further measurement consisted in monitoring of displacement of the fatigue machine hydraulic ram, which is a usual method commonly used.

Static strength of the studs was 621 ± 32 kN, which satisfied design loads with a considerable safety coefficient. However, the damage accumulation monitoring provided important information on certain irreversible changes, internal damage, which could not be observed if the tests were performed by a standard method – static loading with just load and ram displacement records. A typical example of surface strain dependence on static load is shown in Fig. 3. Distinct significant discontinuities of load/strain dependencies at some of the surface points, occurring at loads considerable lower than the maximum strength, about 65% are evident. These discontinuities indicate some internal irreversible damage of the joint near the position of the strain gauges, where

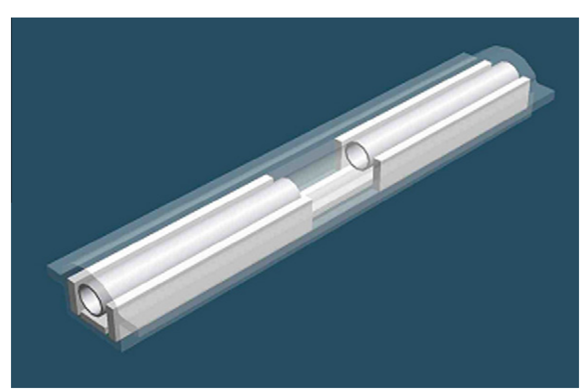

Fig. 1. Schematic view of the full scale stud joint model.