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COMPARING THE CLASSIFICATION OF THE FATIGUE STRENGTH BEHAVIOUR OF SMALL SPECIMENS AND LARGE SCALE COMPONENTS

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COMPARING THE CLASSIFCATION OF THE FATIGUE STRENGTH BEHAVIOUR OF SMALL SPECIMENS AND LARGE-SCALE COMPONENTS

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1. Introduction

In developing a device which is subject to mechanical loads, the engineer is faced with two principle tasks:

- Choice of structure dimensions and materials.
  (Design)

- Proof of structural and mechanical integrity of each component under all appered loads for a certain period of time.
  (Proof Calculations)

In order to accomplish these two tasks three things must be known or estimated:

- Value and time history of all external loads including environmental influences.
  (Assumed Loads)

- Value and time history of the stresses in the structure.
  (Determination of Stress)

- The limit and allowable stresses.

This report is concerned in particular with the last item. The limit strength of a component can only be determined experimentally (if failure through exceeding a stability limit is excluded). Figure 1 shows schematically the place of a small specimen in the development of a structure.

The limit strength of the component can be determined through a test of the actual specimen, this however, is not recommendable for the following reasons:

1) To design a component, it would have to be built in various models, e.g. wall strengths and materials, in order to define the required dimensions and the materials through the test.

2) If a component is under a time varying load, it is well known that different lifetimes can result even with the same model and same load time history. There is a natural scatter effect caused by material and design. In order to arrive at reliable values for the loads, a great many test would have to be performed.

This procedure is not acceptable for reasons of economy.

The only way for a development engineer to accomplish his main tasks, i.e.:

- Dimensioning the structure, selection of materials and

- Demonstration of structural integrity in an economical manner is through the use of small test specimens. A series of data values is determined through vibration strenght tests of small, and therefore cheap specimens which must meet certain specifications given later. In this way only a small number of tests must be performed with the actual components. The prerequisite for this is the establishment of a correlation between the test results with small specimens and the full-scale components.

Up to now the use of small specimens was seen from the development engineer's standpoint only. However in many cases the manufacturing engineer must fall back on specimens tests in order to solve some of his problems. His task (among other things) is to guarantee the product quality via quality control. To this end destructive and non-destructive tests are employed.

For example, quality control of rotor blades made of a composite is not possible with non-destructive tests.

Furthermore, a destructive test of entire blades or blade sections is not acceptable for cost reasons. Thus an economical quality control is only possible through the testing of small specimens. The correlation small specimen test results with the full-scale component is known from development.

The following is a report on experience and development methodology for integrating small scale specimen tests into the overall development program by the Helicopter Division of the Messerschmitt-Bölkow-Blohm GmbH. The development of this methodology forms an essential part of the divisions overall development philosophy.

2. Prerequisite for Correlating the Results of Small Specimen Tests with the Full-Scale Components

In order to correlate the results of small specimen tests with the full-scale component, the following conditions must be met:

- The external and internal loads on the full-scale component must be known.
- The small specimen must be modeled to some extent after the full-scale component and must also demonstrate the same environmental behaviour.
- Damage and failure hypotheses must be known.

A more detailed explanation of these items follows in the next section.

1. Load Prediction for the Full-Scale Component

Upon establishment of the structure configuration a determination of external loads must be performed. The following are defined as external loads:

- mechanical loads (static and dynamic)
- thermal loads (stationary and dynamic)
- environmental loads (erosive, corrosive, weathering).

In general, these loads are not known for a new piece of equipment and thus must be determined, e.g. through theoretical calculations. The results of such investigations are summarized to form the general load conditions for the component in question.

The mechanical - and often the thermal - loads cause stresses in components, which must be known in order to correlate results of specimen tests with the actual component, whether for dimensioning or demonstration strength. The stresses are determined using elasto-mechanics methods.

To determine the dimensions of the structure, the internal geometry of the structure (e.g. sheet metal thicknesses) is determined in an iteration process from the external loads and allowable stresses. And conversely, when demonstrating the strength, actual stresses are determined and then compared with the allowable stresses for a given internal geometry and estimated, calculated, or prescribed external loads.

In addition to the stresses due to external loads, the temperatures and temperature distributions in the full-scale component must be calculated or estimated. It is well known that with practically all materials there is a notable drop in strength with rising temperature. Only results of tests performed at approximately the same temperature are useful in dimensioning the component or demonstrating its strength.

Temperature differences in the component can also cause thermal stresses, as indicated above. In order to determine these stresses, the values, distribution, and changes of temperature must be known.

The third main type of load indicated was the environmental load. These loads are in egeneral erosive, e.g. sand or rain erosion, corrosive, e.g. salt water atmosphere, or general weathering loads.

Erosive and corrosive loads caused from the outside are in general avoided or at least reduced through suitable design me measures are, for example, protective paint coatings or the composites used for erosion protection of rotor blades.

It should be mentioned here that there can be a great deal of internal erosive and corrosive loading on the material at the joints of a component, which is known as friction corrosion with alternating loads. In addition, aging can exert a great influence on the characteristics of the material.

In the section above it was shown that small specimen test results (among other things) can be correlated with the full-scale component when the following is known or calculated for the component:

- The external mechanical, thermal, and other physico-chemical loads, and
- The stresses caused by these loads.

Exact knowledge of the tolerable stresses and their scatter, determined through specimens, is of little value if the actual stresses and conditions in the component are not known.

2. Modeling of Specimen

We have already seen that in general the tolerable stresses and their scatter can only be determined experimentally. This is done with tests of small specimens for reasons of economy. A correlation of these test results with the full-scale component is admissible only when the most important design and technological parameters, such as tolerable stresses and their scatter in the specimen, can be modeled after the actual component.

The most significant parameters affecting the tolerable stresses and their scatter are:

- Design Parameters
  - Stress Concentration Factor (=s.c.factor)

- Combination of Materials
- Tolerances
- Scales

- Technological Parameters
  - Manufacturing Processes
  - Condition of Material
  - Internal Stress
  - Fiber Pattern

The influence of the s.c. factor is generally well known. Unfortunately the s.c. factors have different values dependant upon the design. This is handled by establishing standard s.c. factors and testing of sample bars notched in in accordance with these standard s.c. factors. It is obvious that the best design is one with the smallest s.c. factors. The general natures of the sample bar tests since performed allows the application of their results to many and varied problems.

Fig. 2 shows the results of a test series performed with notched samples of Ti 6 V4. The s.c. factor was 3.2. A preliminary regression curve equation was determined from these tests, cf. (1). The standarddeviation for the tests was $S = 1.075$ kg/mm^2. From this, according to statistical procedures, the allowable stresses for dimensioning a full-scale component can be derived.

Just as important as the s.c. factor is proper materials combination, if tolerable stresses and their scatter are to be determined through small specimen tests for force input and force transfer elements, such as a tie rod for example. The serious friction corrosion problems of tie rods are well known. The friction corrosion behaviour and thus the vibration strength are decisively influenced by the selection of materials combinations. Fig. 3 shows results for Ti 6 Al 4 V. It was possible to approximately double the value of tolerable stresses, without changing the lifetime, by silver-plating the steel bushings, i.e. by changing the material combination. For comparison, the characteristics of tie-rods with a different s.c. factor (s.c. factor according to Larsson (2)) were also given.

Structures of glassfiber reinforced palstic are often built up by layers of different fiber orientation or different fiber materials. This materials combination of the composite must be simulated with the specimen.

Less well known, but just as important, is the influence of tolerance. Here, too results from a test series with tie-rods made of Ti 6 Al 4 V are given as an example, cf. Fig. 4. The fits were varied for the sleeve and borehole in such a manner as to vary the interference between the sleeve and the borehole. Although the results do not have a firm statistical basis, due to an insufficient number of tests to failure, the essential curve form is known from tests with other materials, and thus the determination of the optimum value is possible.

The scale was given as the final important design parameter.
The scale does not always have an effect on the test results. However, in general a check should be made to see if such an influence exists when results from small specimens are to be correlated with full-scale components. Reference should be made here to a book (3) by Prof. Hertel, from which some points have been taken over directly.

The following paramenters which influence the vibration strength of the components, show a dependance upon the absolute size of the tested specimen vibration.

- Stress gradient at the point of the maximum stress
- Cycles from initial damage to failure
- Size of the relative motion in friction corrosion problems
- Surface influence

Concerning the first point, test results should be given as example. For further explanations and a detailed description, refer to (3). It is well known that there is a mutual supporting effect of adjacent fiber with a varying stress distribution across the speciment or component. Therefore, the tolerable stresses determined in a tensile strength test are to be considered as minumum stresses. Figure 5 shows the relationship of the allowable bending strain to the allowable axial load for fiberglass as a function of the cycles to failure and the stress conditions. The allowable bending stress can be up to 1.8 times the pure normal stress. This gradient depends on the absolute size of the specimen with respect to component, because the stress gradient in bending is the same as the ratio of the bending stress to half the height of the specimen or component. The values ascertained by means of a small bending test specimen at relatively high stress gradients and the purely shear test specimen at constant stress represent the two boundary values.

Having illustrated the influence of design parameters by some examples- let us turn to the influence of the technological paramenters.

In considering technological parameters, the manufacturing process is of great importance. Small deviations in the manufacturing technology can lead to large differences in the strengths. Figure 6 gives an example from composites technology.

A comparison is made of the results of tests with short shear test specimen which were manufactured using the following processes:

- manual manufacture
- semimechanical quantity manufacture (rotor blade)
- laboratory manufacture

Specimens manufactured by a purely manual method, were accompanied by uncontrollable fiber impregnation, and thus yielded the worst results and the highest degree of scatter in proportion to the low number of cycles to failure. Semimechanical manufacture, compared to laboratory manufacture showed a certain decrease in scatter. The values shown illustrate the qualitative dependence of the shear stresses on the manufacturing process. Of interest is the fact that the fiber content was approximately the same for all specimens.

The influence played by the other technological parameters is generally known and needs therefore not be discussed further. It should only be mentioned, however, that the correct simulation of internal tension conditions, for instance in the small specimen because of surface treatment, is exceedingly difficult if not almost impossible.

This section discussed the significant parameters which must be taken into consideration for correct simulation in order to relate the results of small-specimen tests to the full-scale component.

3. Failure Hypotheses, Damage Accumulation Hypotheses

A knowledge of damage accumulation and failure hypothesis is a further important prerequisite for use of small-specimen test results for dimensioning or verification of full-scale components. Small-specimen tests are either conducted as single-stage tests or as multistage tests with a certain fixed load condition.

The chronological order and the size of the loads in the full-scale component varies considerably. Thus application of small-specimen test results is only possible by

- load classification and frequency determination
- application of damage accumulation hypotheses

The so-called Miner Theory is the best-known and most frequently applied damage accumulation hypothesis. It's simplicity makes it also most suitable to dimensioning of components.

In order to check the Miner Theory as to its applicability with special regard to high numbers of cycles to failure, the results from 111 single-stage tests and 56 multistage tests conducted in the Labor für Betriebsfestigkeit (LBF) (Serviceability Laboratory) were evaluated and compared using the Miner Theory (5). The result is given in Figure 7. It is seen that the Miner hypothesis gives somewhat optimistic values for the endurance strength range and thus should be used with some caution. This method should only be employed in the absence of friction corrosion.

In this chapter, only a few remarks were made about the applicability of procedures which are necessary in this presentation. This problem is dealt within detail in the extensive works of Prof. Gassner and others.

3. Comparison of the Metal and Composites

The following is a comparison of the two currently most important materials, namely metal and composites. The important differences are:

- dependence of stress direction on the mechanical properties
- stress concentration factor, notch sensitivity, crack propogation, and
- vibration strength.

Composites show strong anistropy of the elasticity constants and of the strength properties, the metals, are largely isotropic. Elasticity constants and strength properties of composites are strongly anisotropic, whereas metals are largely isotropic. Hence by using composites the designer can optimize with respect to both dynamics and strength. Figure 8 shows the important properties of composites in qualitative form.

Together with the strong directionality of mechanical properties in composites, the difference in the amount of the notch factor, the notch sensitivity and of crack propogation as compared to metals should be mentioned.

A static test on a perforated fiberglass-reinforced-plastic bar and on a perforated steel bar (see Figure 9) gave a notch factor k = 3.0 for fiberglass-reinforced plastic and k = 2.4 for steel in tension and k = 2.4 and 1.7 on bending. The notch factor is thus greater with undirectional (orthotropic) composites than with metal. This does not yet imply anything as far as strength is concerned. As a result of dynamic or static loads which exceed the shear strength, the undirectional fiberglass-reinforced plastic bar breaks parallel to the fiber direction and not, as does metal, normal to the edge. Thus the notch effect is very quickly reduced; Figure 10 illustrates the significance of this in regard to strength. It should be noted that tolerable stresses for the notched and the unnotched bar are practically the same.

An additional difference between composites and metal is demostrated by the vibration strength (see Figure 11), especially in the range of high numbers of cycles to failure.

There the tolerable stresses for composites are extremely high as compared to metals. The inclination of the S-N curves is far flatter than with metal, especially with carbonfiber- reinforced plastics. With customary evaluation methods this results in too large a scatter in the fatigue life values. In order to make reasonable statements as to tolerable stresses, new evaluation procedures had to be developed. These procedures are essentially based on the fact that a regression curve equation is established from the test results and that the evaluation is effected through the stresses at a constant fatigue life and not fatigue life at constant stress.

The test results can then be evaluated by application of statistical pronciples. This procedure is described in greater detail in (1).

4. An Example from the Development of the Bölkow Rigid Rotor System

The following example shows how the vibration strength tests with small specimens were an integral part of the overall development and testing in the case of the Bölkow rigid rotor system development (6).

The idea of this rotor system is to eliminate the flapping and drag hinges of the blade by utilizing an extermely strong, but very elastic material. FRP is especially suitable for this.

From previous development work sufficient knowledge of allowable stresses for FRP has been accumulated to allow a preliminary dimensioning of the rotor blades after the first load conditions were fixed based on aerodynamic and flight-mechanical investigations.

The manufacturing process was also defined at this stage of development. A so-called wet-in-wet technique with a hot-curing epoxy system was chosen. Figure 12 shows the blade section. The blade consists of a C spar of unidirectional FRP to absorb the centrifugal forces and bending moments. The torsional moments are absorbed principally by the outer FRP layer. The remaining part of the blade section is filled with low-density foam.

In order to perform a final dimensioning and stress analysis of the rotor blades, the following questions had to be answered for this special material and manufacturing process:

- how great are the tolerable normal stresses under tensible and bending loads
- how great are the tolerable shear stresses
- how great is the scatter of the tolerable stresses
- what is the influence of aging, weathering and temperature.

An extensive program was conducted with small specimens to clarify these questions. This program was concerned especially with the unidirectional FRP of the spar, because the skin was dimensioned for expected stiffness requirements and strength problems were not anticipated.

In order to ensure that all parameters are correctly considered it was decided to manufacture original rotor blades, or blade portions and to cut the small specimens from these.

The tests were conducted with three different types of specimen:

- specimen for shear test, a bending specimen of very high ratio of thickness to width for testing shear of the matrix resp. fiber-matrix bonding
- specimen for bending test with normal ratio of thickness to width
- test specimen with waisted section, smooth radii, for normal load tests.

The results of these tests are shown in Figures 13 and 14. The given stresses are admissible values and apply for a survival probability of 99.99%.

Hence, taking the manufacturing technology into account, the tolerable stresses and their scatter were known.

At the same time tests were conducted to determine the influence of aging, weathering and temperature. These revealed no critical influences.

In the meantime the test devices for the full-scale component - here the rotor blade - had been set up and component testing for final design optimization and stress analysis conducted. Figure 15 illustrates the results of the 18 blade root tests. The blade root was modified twice, each time improving the fatigue strength. For this reason all test points were included in the final evaluation.

A standard deviation of 1.1 was used

for the establishment of admissible moments. This value was the result of the small-specimen tests.

If one consideres that a new material was utilized for the rotor blade and a novel design solution applied to the blade root, one will realize that, comparatively speaking, conducting 18 tests with the full-scale component represents relatively low expenditure. This was only made possible through integrating small-specimen tests into the development stage.

5. Summary

This paper first of all gave a justification for conducting extensive fatigue strength tests with small specimens. In addition, those prerequisites were given which enable the results of these small-specimen fatigue strength tests to be related to the full-scale component. This gives on the one hand an exact forecast of the stress condition in the full-scale component and on the other hand an exact simulation of the design and technological parameters into the small-specimen.

A further section dealt with a systematic comparison of both base materials used today in aircraft construction, metal and composites. Special problems in the development of dynamically stressed structures made of composites were illustrated. Solving these problems is only possible through small-specimen testing.

The last section gave information on test results during the development of the Bölkow rigid rotor system.

A short description of the development of the design concept to the completed full-scale component of a production helicopter was given. Emphasis was agein placed on the importance of fatigue strength tests with specimens and the necessity of their integration into the overall development of a full-scale component.

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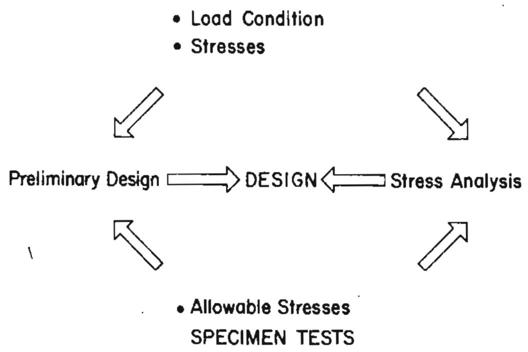


Fig. 1: Transfer of Specimen Test Results of Actual Structure

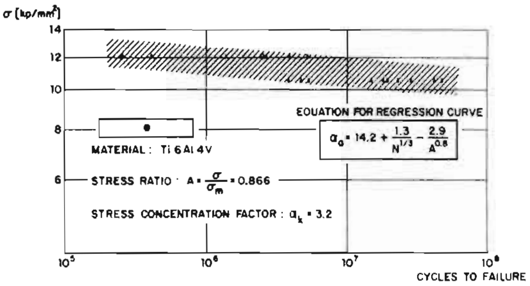


Fig. 2: Fatigue Characteristic of Notched Specimen

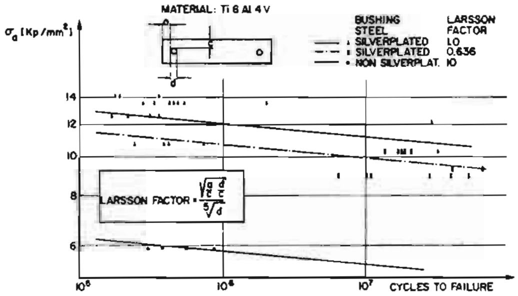


Fig. 3: Fatigue Characteristic of Lugs

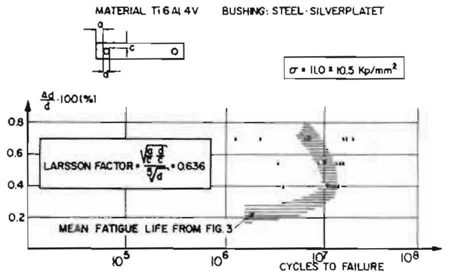


Fig. 4: Effect of Interference Bushing-Hole on Fatigue Life of Lug

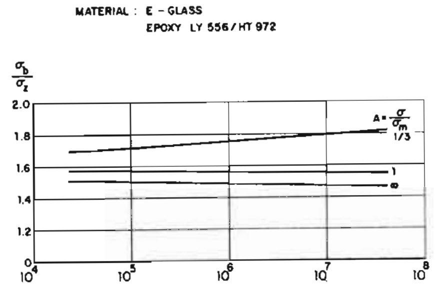


Fig. 5: Bending Strength to Tension Strength

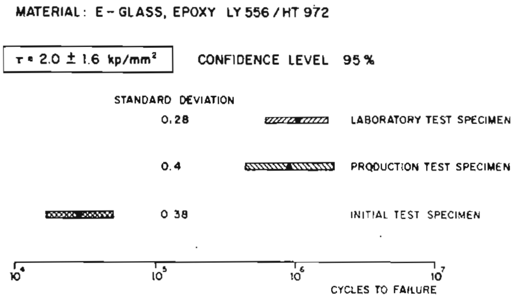


Fig. 6: Influence of Processing on Fatigue Life

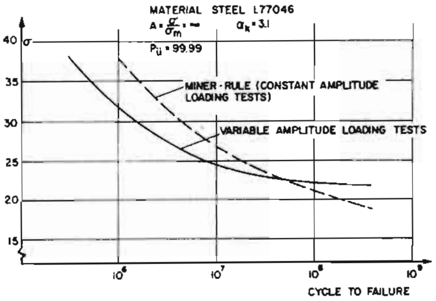


Fig. 7: Comparison of Miner-Rule with Variable Amplitude Loading Tests

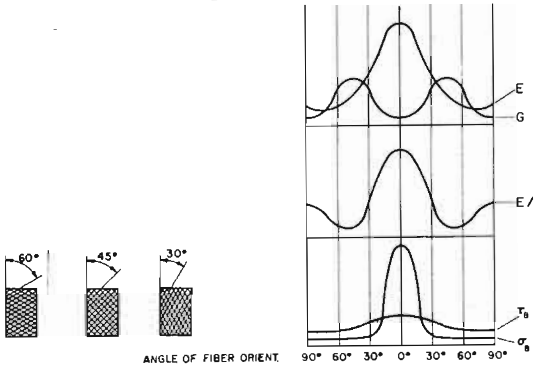


Fig. 8: Effect of Fiber Orientation of Youngs Modulus, Shear Modulus & Strength Reinforced Plastics

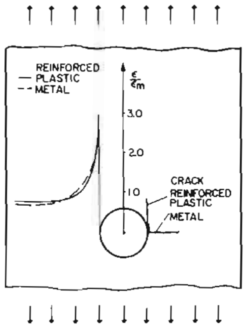


Fig. 9: Strain Distribution in Notched Bar

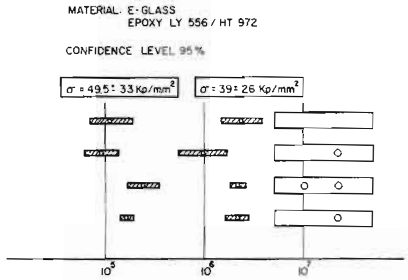


Fig.10: Influence of Notches on Fatigue Life of Reinforced Plastics

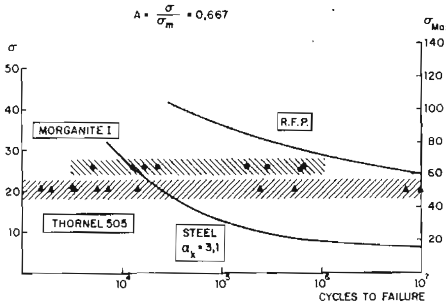


Fig.11: Comparison of S-N-Curves of Steel, to Glass and Carbonfibers Reinforced Plastics

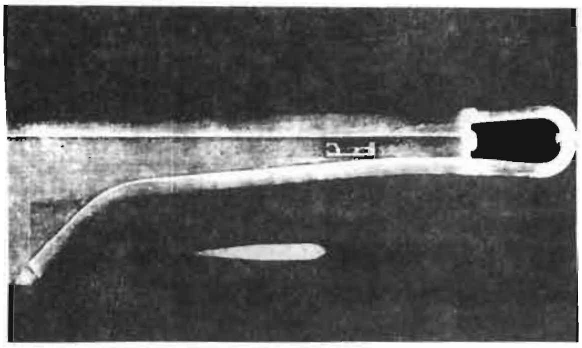
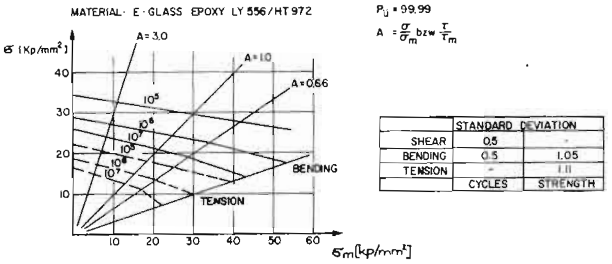


Fig.12: Rotor Blade of the BO 105 Root and Cross Section



	STANDARD DEVIATION	
SHEAR	0.5	-
BENDING	0.5	1.05
TENSION	-	1.11
	CYCLES	STRENGTH

Fig.13: Allowables for Reinforced Plastics

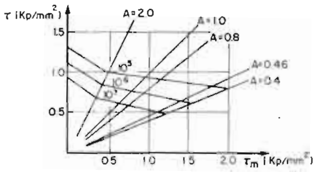


Fig.14: Allowables for Reinforced Plastics

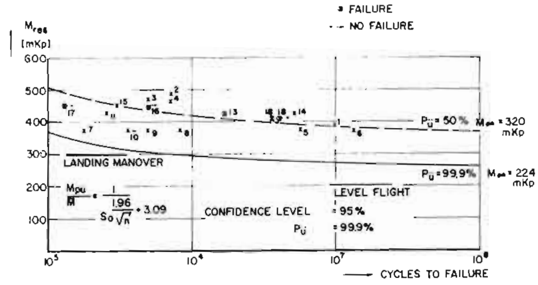


Fig.15: Allowables of FRP-Rotorblade of BO 105 (Root)

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