NREL/CP-440-23257 • UC Category: 1213

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Presented at Windpower '97
Austin, Texas
June 15–18, 1997

National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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USING PARTIAL SAFETY FACTORS IN WIND TURBINE DESIGN AND TESTING

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ABSTRACT

This paper describes the relationship between wind turbine design and testing in terms of the certification process. An overview of the current status of international certification is given along with a description of limit-state design basics. Wind turbine rotor blades are used to illustrate the principles discussed. These concepts are related to both International Electrotechnical Commission and Germanischer Lloyd design standards, and are covered using schematic representations of statistical load and material strength distributions. Wherever possible, interpretations of the partial safety factors are given with descriptions of their intended meaning. Under some circumstances, the authors' interpretations may be subjective. Next, the test-load factors are described in concept and then related to the design factors. Using technical arguments, it is shown that some of the design factors for both load and materials must be used in the test loading, but some should not be used. In addition, some test factors not used in the design may be necessary for an accurate test of the design. The results show that if the design assumptions do not clearly state the effects and uncertainties that are covered by the design's partial safety factors, outside parties such as test labs or certification agencies could impose their own meaning on these factors.

INTRODUCTION

The use of partial safety factors in wind turbine design is common practice and is, in principle, accepted by International Electrotechnical Commission (IEC) and other international organizations as a practical means for achieving sound designs [1]. The technique stems from an ISO standard on limit-state design theory, which describes actions (loads) and resistances (strengths) associated with a structure [2]. In the design process, partial safety factors are applied to either the loads or the strengths to account for their respective uncertainties. Throughout the world, numerous design codes exist that specify the various partial safety factors to be applied, however little agreement exists among the available codes [3]. This creates a problem if certain codes are to be recognized outside their traditional boundaries. The problem is complicated more when insufficient background or guidance is given to describe how a partial safety factor is to be applied and what influence or uncertainty it accounts for. Sometimes a factor's intended purpose may be intentionally vague, or at least poorly understood. This may give designers some needed flexibility and may keep the codes from becoming too restrictive, but these ambiguities do not help the designer account for the true uncertainties represented by each partial safety factor or assure consistency between design approaches.

During a test, the best possible loading would produce a true representation of the intended design conditions. To develop the equivalent full-scale test loading for design verification, a combination of design safety factors and test-load factors are required. A test-load factor is applied on top of the design loads to account for design conditions not properly represented by the test. For example, test environments are less severe than operating conditions and this difference can be accounted for using a test-load factor. Also, uncertainty that is introduced when modifying the design loads to establish simplified and elevated test loads for the purpose of accelerating the test can warrant an additional test-load factor. These factors should be applied appropriately if the design is to be honestly evaluated. But this may not be possible unless each influence covered by the partial safety factor in both the design and test is known and accounted for explicitly. Otherwise, these influences could easily be overlooked, or double-booked, when establishing the test conditions.

Wind turbine blades are among the most critical components in the turbine design and provide a good basis for illustrating the application of partial safety factors for different design codes. For this paper, the discussion will focus on the rotor blade design and testing.

CERTIFICATION BACKGROUND

International certification has become a requirement for U.S. manufacturers to compete in many foreign markets. At present there are three international certification bodies active in the European wind turbine industry: Germanischer Lloyd (GL), Det Norske Veritas and Risø, and CIWI. Each certification body has developed its own interpretation, and therefore rules and requirements for Type Certification, the process by which a specific turbine type is certified by independent review of design, testing, and manufacturing documents and records. One of the more consequential differences among the different organizations' rules is the treatment of partial safety factors.

Recognizing the problem, the European Community (EC) encouraged harmonization of the different certification rules in order to facilitate trade within Europe. Over the past 5 years, this has resulted in active standards development programs on the international level. The IEC has supported the development of several standards that are intended to be the basis for a set of harmonized standards. European certification bodies plan to take a step toward harmonization by adopting the IEC standard in addition to their own national requirements in the future. Within the EC, certification procedures will still likely depend on national requirements, but the IEC international standards will be the basis for international certification procedures.

Certification of wind turbines in the U. S. is not required. As a result, most U.S. turbine manufactures did not pursue certification until recently. Because the international market is now stronger than the domestic market, interest in certification by U.S. manufacturers has increased; however, there currently is no U.S. certification body, nor is there an established set of U.S. standards on which to base a certification process. The National Renewable Energy Laboratory (NREL) and the American Wind Energy Association have been active in the IEC standards development effort in anticipation of using these standards in a U.S. certification program. NREL has developed certification testing capability and design review requirements that conform to IEC Type Certification requirements.

LIMIT-STATE DESIGN

The IEC 1400-1 wind turbine design standard is based on ISO 2394 "General Principles on Reliability for Structures." This standard specifies limit-state design procedures that use partial safety factors to manage uncertainty in various steps in the design process. The partial safety factors are dependent on the uncertainties in loads and materials, the uncertainties in the analysis methods, and the importance of structural components with respect to the consequences of their failure.

To assure safe design values for loads and material properties, the uncertainties and variability in load predictions (characteristic load values) and material properties (characteristic strength properties) are adjusted by partial load and material design factors. In IEC 1400-1 the alternative term "representative value" is used in some cases, where a characteristic value is not easily evaluated statistically.

Equation 1 defines design loads and Equation 2 defines design material properties according to ISO 2394 and IEC 1400-1.

$$F_d = \gamma_f F_k \tag{1}$$

where:

F_d are the design values for loads

γ_f are the partial load factors

F_k are the characteristic values for loads.

$$f_d = \frac{1}{\gamma_m} f_k \tag{2}$$

where:

f_d are the design values for material properties

γ_m are the partial material factors

f_k are the characteristic values (e.g., strength) of material properties.

A consequences of failure partial safety factor, γ_n, is adopted in IEC 1400-1 to distinguish between:

Component class 1: Used for "fail-safe" structural components whose failure does not result in the failure of a major part of a wind turbine generator system (WTGS);

Component class 2: Used for "non fail-safe" structural components whose failures lead rapidly to the failure of a major part of a WTGS.

Typically, γ_n is applied to class 2 components, such as wind turbine blades, which are not fail-safe by design.

The general equation for non-exceedance of the ultimate limit-state [2] is:

$$\gamma_n \cdot S(F_d) \leq R(f_d) \tag{3}$$

Each type of analysis requires a different formulation of the load and strength functions, S and R respectively, and deals with different sources of uncertainties through the use of safety factors. In general, static-strength design cases are usually evaluated with a different set of factors than the fatigue design cases, because the failure modes are different and the uncertainties are dependent on the type of loading used. Equation 3 is important to the following discussion, especially in developing the test loading, because it shows that the partial safety factor for consequences of failure is applied to the load (left) side of the equation.

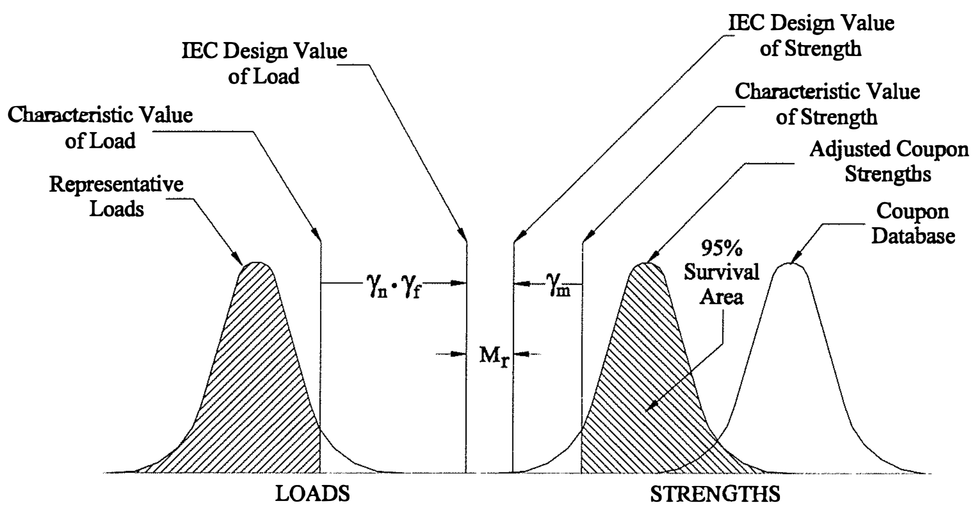
Most design codes address partial safety factors for both load and strength individually and in accordance with Equations 1 and 2. According to IEC 1400-1, the partial load safety factors are meant to account for the possibility of unfavorable deviations of the load from the characteristic value, and uncertainties in the loading model. The partial material safety factors are meant to account for the possibility of unfavorable deviations of material strength from the characteristic value, inaccurate prediction of the load-carrying capacity of the structure, uncertainties in geometry, and uncertainties in converting the material properties measured on the test control specimens (coupons) to the material properties of the structure.

Of primary importance with the design-application of material partial safety factors is the adjustment of composite material properties from small coupon data to the full-scale structure. Material property adjustments may be necessary to correct for the effects of moisture, temperature, ultraviolet radiation, creep, scale effects, material volume, manufacturing variability, defects, and fiber content. Most of these have an unfavorable influence on strength and are given by design standards as reduction factors. A material factor may also be necessary to account for uncertainty in the strength or fatigue formulations used to convert the operating load spectra into life or strength.

Some codes account for these different influences individually, using separate safety factors for each concern, but generally offer weak rationale. Others lump the load-related uncertainties into one factor, γ_f, and the material related factors into another factor, γ_m. For blade design verification tests, some of the design partial safety factors are applied to the test load and some are not. To represent the test load accurately, the material partial safety factor in the design must be subdivided into smaller components so that the uncertainties that are accurately accounted for in the test can be separated from those that are not. Most design codes do not recognize this constraint. This paper gives clarification on how partial material factors and consequences of failure factors should be applied for blade testing to avoid inconsistent accounting of the various factors by testing organizations, certification organizations, and designers.

IEC1400-1 - PARTIAL SAFETY FACTORS

Figure 1 gives a schematic representation of the IEC 1400-1 design safety standards for both static and fatigue cases as they existed in the April 1997 draft revision. The sample cases shown are for wind turbines having ultimate limit loads driven by extreme aerodynamic forces. The standard assumes that the material strength data is normally distributed with a 10% coefficient of variation (COV), but it gives guidance for other COVs when data is available.



Partial Safety Factors:

γ_f - Load Uncertainty (1.1 for fatigue and 1.35 for ultimate strength)

γ_n - Consequences of Failure (1.15 for fatigue and 1.0 for ultimate strength)

γ_m - Materials Strength Uncertainty (1.10 with 95% survival, 95% confidence, 0.1 COV)

M_r - Reserve Margin

FIGURE 1 - APPLICATION OF IEC 1400-1 PARTIAL SAFETY FACTORS

The IEC 1400-1 design safety standards require a minimum partial safety factor of 1.1 to be applied to account for uncertainty (non-deterministic influences) in shifting from the material coupon strengths to manufactured blade strengths for both ultimate strength and fatigue analysis. Before this factor is applied, however, the coupon strengths must already be corrected to account for a number of more deterministic influences including, scale effects, creep, degradation due to external actions (e.g., humidity, temperature, ultraviolet radiation), and defects that would not normally be detected (e.g., fiber alignment, fiber volume). In addition, the characteristic coupon strengths are also adjusted beforehand to a 95% survival probability with 95% confidence for the assumed COV of 10%.

IEC 1400-1 does not give procedures or partial safety factors for making coupon strength corrections to account for the numerous deterministic adjustments listed above. Designers are left to develop their own adjustments based on independent testing, published test data, or analysis, and provide the sufficient justifications [e.g., 4, 5, 6, 7]. This process can be complex and laborious, but may be advantageous for design optimization, because material property adjustments are very dependent on the specific materials used and the details of the design. Therefore the adjustments are best if determined on a case-by-case basis. This adjustment is illustrated in the figure as the difference between the coupon strength database distribution and the adjusted coupon strength distribution. The final partial safety factor of 1.1 is applied only to account for the uncertainty in shifting from the corrected coupon strengths to the actual blade.

The partial load factors for ultimate limit-state load cases range from 1.1 to 1.45, depending on the source of loading, and is given in tabular form in IEC 1400-1. Most commonly, the source of the extreme loads would be aerodynamic, such as with an extreme gust event, operational, such as a high wind shutdown. The factors used for these events would be 1.35 and 1.45, respectively. No adjustment is required under IEC rules to cover the consequences of failure for ultimate limit-state cases.

For fatigue, no partial safety factor is required to directly cover load uncertainty. However, a partial safety factor of 1.15 is required to cover the consequences of failure, γ_n, for rotor blades because they are non-fail-safe components. Based on ISO 2394, the partial safety factor, γ_n, can be considered a load factor because it is applied to the load function, $S(F_d)$, in Equation 3.

For IEC 1400-1, the product of all the partial safety factors combined is greater in the ultimate case ($\gamma_{n,} \cdot \gamma_m \cdot \gamma_f = 1.485$) than in the fatigue case ($\gamma_{n,} \cdot \gamma_m \cdot \gamma_f = 1.265$). However, it is impossible to assign a number that represents the total design adjustments made for either IEC case, because most of the material adjustments, which are design dependent, are not explicitly specified. The 1.1 material factor is only given as a minimum starting point.

GERMANISCHER LLOYD - PARTIAL SAFETY FACTORS

The German certifying agency, Germanischer Lloyd (GL), has a design code that is often used by wind turbine manufacturers for certification [8]. Figure 2 gives a schematic representation of our interpretations of the GL Standard from Chapter 5 on rotor blades, for both ultimate strength and fatigue cases using glass reinforced plastics (GRP). Other materials are addressed, but the bulk of the code deals with GRP blades.

In contrast to the IEC, the GL standard prescribes all of the individual factors to be applied for each influence of concern on the material side. None of the adjustments are left to the designer, however, the meaning of each factor is not always fully given.

Both the ultimate strength and the fatigue cases use the static coupon strengths as a basis. For the ultimate limit-state, or strength verification, a series of five partial safety factors are given: C_{1a}, C_{2a}, C_{3a}, C_{4a}, and C_{5a}. As shown in Figure 2, the product of these factors, γ_m, is applied to the material strengths, as in Equation 2. The first factor, C_{1a}, is a general safety factor of 1.35 and may, in the authors' opinion, cover such influences as consequences of failure, modeling uncertainty, scale effects, and manufacturing defects. The exact purpose of this factor is not specified.

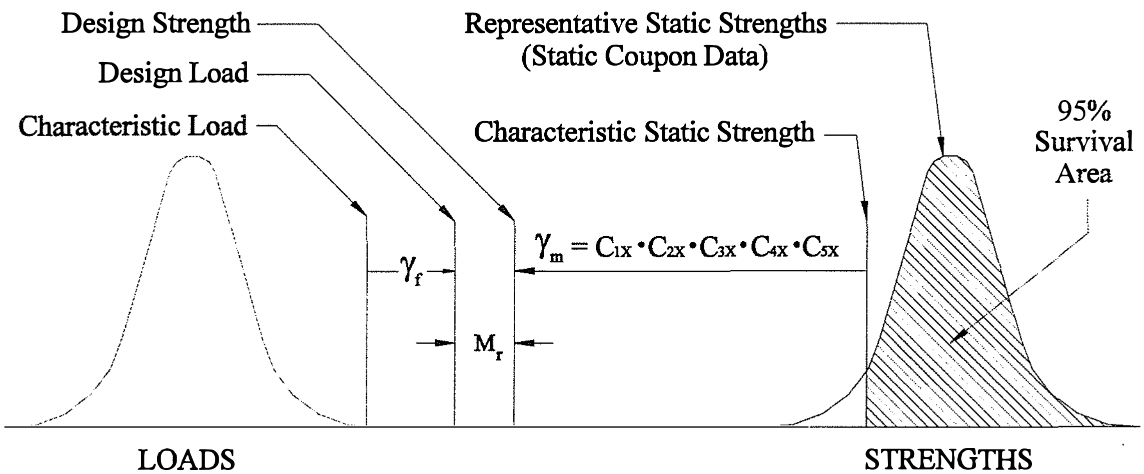


FIGURE 2 - GERMANISCHER LLOYD PARTIAL SAFETY FACTORS FOR ROTOR BLADES

A value of 1.5 is assigned to C_{2a} to account for creep strength, but a more elaborate description is not given. A value of 1.1 is applied to C_{3a} to account for temperature effects in the operating environment. C_{4a} accounts for the laminate quality where prepregs are given preference over hand layups. The values assigned to these factors are 1.1 and 1.2, respectively. Finally, C_{5a} is a factor used to account for uncertainties in the resin cure method used. Tempered laminates are not penalized, while untempered laminates require a factor of 1.1 to be applied. The product of these material factors results in a total factor for ultimate strength of between 2.45 and 2.94, applied to the characteristic values of coupon strength with a 95% probability of survival.

For fatigue, a similar series of partial safety factors is given as C_{1b},C_{2b}, C_{3b}, C_{4b}, and C_{5b}. The first factor, C_{1b}, is the general safety factor of 1.35. In addition to the influences listed for the strength verification case, this factor may cover uncertainty of material properties for the given lifetime, or uncertainty in the fatigue formulations used (e.g., Goodman relations, Miner's summation). The factor C_{2b} gives specific guidance for shifting the static coupon strengths to fatigue strengths for either epoxy or polyester matrices. As with the ultimate case, C_{3b} deals with temperature effects in the operating environment and is assigned a value of 1.1. C_{4b} addresses fiber alignment and fatigue sensitivity by penalizing blades made from woven or non-continuous fibers with a factor of 1.2. Blades made from continuous, non-woven fibers have a factor of 1.0. C_{5b} is identical to the factor, C_{5a}, in the ultimate strength case. The product of these material factors results in a total fatigue factor of between 1.485 and 1.96 that is applied to the uncorrected coupon fatigue strengths (excluding C_{2b}).

The partial safety factor on loads required by Germanischer Lloyd to verify the ultimate strength case is 1.35 for the aerodynamic case in this discussion. For the GL fatigue case, a factor of 1.0 is used. This is the same as for the IEC fatigue case. However, the GL standard does not explicitly give a factor to cover consequences of failure for fatigue or ultimate strength.

IEC/GL COMPARISON

One way to judge the severity or conservatism of any code is to look at the product of the material and the load factors. This product will determine the margin between the loads and the strengths. Because GL prescribes the values to be used in correcting for each material effect, and IEC allows most of the corrections to be made by the designer, a direct comparison of total partial safety factors is difficult. But for the purposes of this discussion, it is worthwhile to make an attempt at this comparison in rough measures.

Tables 1 and 2 summarize the explicitly stated design partial factors for both the IEC and GL codes, for ultimate strength and fatigue.

TABLE 1 – PARTIAL SAFETY FACTORS FOR ULTIMATE STRENGTH ANALYSIS

Partial Safety Factors	*IEC 1400-1*	*Germanischer Lloyd*
Loads	1.35	1.35
Consequences of Failure	1.0	1.0
Materials	1.1*	2.45 – 2.94
Total	1.485*	3.30 – 3.96

* Excluding coupon material property adjustments

TABLE 2 – PARTIAL SAFETY FACTORS FOR FATIGUE ANALYSIS

Partial Safety Factors	*IEC 1400-1*	*Germanischer Lloyd*
Loads	1.0	1.0
Consequences of Failure	1.15	1.0
Materials	1.1*	1.485 – 1.96**
Total	1.265*	1.485 – 1.96**

* Excluding coupon material property adjustments
** Excluding C_{2b}

For ultimate strength, the IEC product of partial safety factors is 1.485. This excludes the material property adjustments, illustrated earlier in Figure 1, which were applied before, γ_m, the minimum material partial safety factor of 1.1. In the GL code, the total product of partial safety factors is between 3.30 and 3.96. Therefore, in order for the two codes to be equal with respect to ultimate strength, IEC designer-specified adjustments of between 2.22 and 2.67 would be necessary on the coupon material properties.

For fatigue, the IEC product of load and material partial safety factors is 1.265, including the factor for consequences of failure. As with the ultimate strength case, this excludes the designer-specified material property adjustments made before, γ_m, the material partial safety factor was applied. In the GL code, the product of partial safety factors is between 1.485 and 1.96, the same as the total material side factor. Making the same argument as the ultimate strength case, the IEC designer-specified material property corrections for fatigue would be between 1.17 and 1.55 to make the two codes equally severe.

As a general observation, it appears that the GL code is more severe with respect to ultimate strength criteria than for fatigue. The IEC ultimate strength and fatigue cases appear to be closer. Because the IEC designer-specified material adjustments add such a large variable it is difficult to determine which code is more severe in each case. From the authors' experience, however, it appears that GL may more stringent in the ultimate strength case where in fatigue IEC may be more stringent. These differences illustrated above can result in design strength differences, but also can cause critical ambiguities in determining the blade test loads used for design verification.

TEST-LOAD FACTORS

Full-scale blade testing has become a common method of verification for wind turbine rotor blades, although there are few codes that require blade testing to be performed at this time. A typical design verification test used for certification checks the blade's ability to withstand an envelope of design load conditions. The test is considered successful if the blade survives the prescribed test loading without a failure. Further information about failure modes, manufacturing quality, and reserve strength can be obtained if the testing is continued to blade failure.

During a test, the best possible loading would produce a true representation of the intended design conditions. To develop the equivalent full-scale test loading for design verification, a combination of design safety factors and test-load factors are required. First the design-load partial safety factors are applied to the characteristic loads, because the same load uncertainties in the design analysis are inherent to the test procedures.

A significant portion of the material-design partial safety factor is ignored for the test loading, because the material in the blade being tested embodies most of the specific material properties that the factors are intended to cover. However, the component of the material-design partial safety factor that accounts for degradation due to environmental effects such as humidity, temperature, and ultraviolet radiation is usually not properly represented in the laboratory conditions. For the purpose of establishing a representative test load, this component of the material partial safety must be applied as a test-load factor.

Additional test-load factors may also be necessary to account for uncertainties introduced by the test equipment and test-load formulations. These uncertainties might arise due to errors in using or applying the S-N or Goodman relations when modifying the test loads to accelerate the test time or to simplify the test loading to fit laboratory equipment limitations [9].

The above approach for establishing the test loads is technically consistent with limit-state design theory, but differences among the various codes in the treatment of design partial safety factors are passed on to the test, and in some cases, amplified. As mentioned earlier, the product of the material and load factors indicates the severity of a given code. But when a large portion of the material factor is ignored for the test, the relative importance of the load factors is increased. Following this approach, two blades with essentially the same design requirements and strength could have significantly different test requirements.

This incongruity is illustrated in Table 3 using the two codes mentioned above. Applying the above method for establishing a fatigue test load, the IEC test loads would probably be higher than the GL test loads. This is because γ_n equal to 1.15, covering consequences of failure, is applied to the IEC test loads, while GL has no load factors. Because environmental effects are treated differently between the two codes, this would cause further differences between the respective test loading.

TABLE 3 – LOAD FACTORS FOR FATIGUE TESTING

Test-load Factors	*IEC 1400-1*	*Germanischer Lloyd*
Design Load Factor	1.0	1.0
Consequences of Failure	1.15	1.0
Materials Factor	Environmental Effects	Environmental Effects
Total Test-load Factor	1.15 x Environmental Effects	Environmental Effects Only

STRENGTH-BASED TESTING

Another approach that is used to develop loading for blade tests is a strength-based method. While this method is more likely to be requested by a blade designer, it can also be used as a design-verification test for certification. More often strength-based test loads are used as a verification of as-built strength. Loading is based on the design material strength properties for the blade structure rather than a design-load envelope, and they are usually less complicated to develop. Strength-based testing tends to load the blade more uniformly in terms of the spanwise strain distribution, and often results in a blade failure. The basic manufacturing and material assumptions are checked when this method is implemented. Figure 3 shows the relationship between the design and test-load factors for both strength and load-based tests.

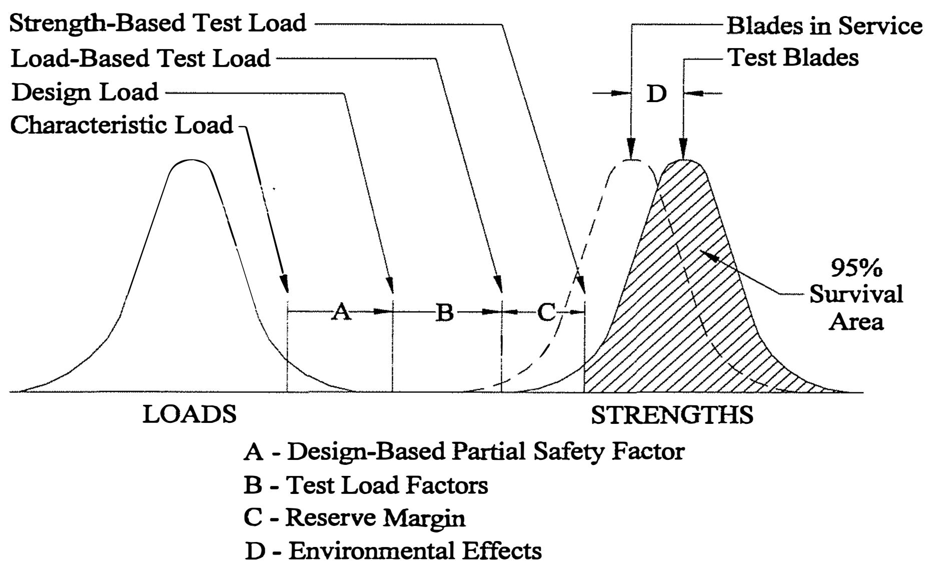


FIGURE 3 - GENERALIZED APPLICATION OF LOAD FACTORS FOR WIND TURBINE TESTING

Note that the strength-based loading is more severe because it includes the blade's reserve strength. Also shown is the relationship between the test blades and the blades in service. The more severe operating environment of the in-service blades lowers their strength.

CONCLUSIONS

This paper describes the growing importance of wind turbine certification in terms of the rotor blades. The latest revision of IEC 1400-1, "Wind Turbine Generator Systems, Part 1: Safety Requirements," is compared to the Germanischer Lloyd counterpart "Non-Marine Technology, Part 1 Wind Energy, Regulation for the Certification of Wind Energy Conversion Systems" by explicitly comparing the rule governing wind turbine blade design. Areas of ambiguity were described. In general, it appears that IEC 1400-1 might have a less conservative treatment of ultimate strength design criteria while the treatment of the fatigue analysis might be more conservative under IEC. This comparison is difficult to confirm, however, because most of the material adjustments made under IEC rules are not explicitly given.

A general procedure given for determining test loading for load-based design verification tests shows that design code differences, particularly in the treatment of partial safety factors, can lead to significant differences in how two blades are tested.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of Scott Hughes, who helped organize this paper and provided essential support in preparing the figures. This work was performed under DOE/NREL prime contract DE-AC36-83CH10093 and the continued support of the U.S. Department of Energy is greatly appreciated.

REFERENCES

1. Bakker, D., International Electro-technical Commission TC88 IEC1400-1: Second Edition 1996-2 "Wind Turbine Generator Systems, Part 1: Safety Requirements," March 1996.

2. ISO 2394, "General Principles on Reliability for Structures," Second Edition - 1986-10-15.

3. Van Grol, H.J., *Strength and Fatigue Testing of Large Size Wind Turbine Rotors" - Vol. 1 Rationale and Directions*, ECN-C-95-052, June 1996.

4. Bulder, B. H., and Bach, P.W., *A Literature Survey on the Effects of Moisture on the Mechanical Properties of Glass and Carbon Fibre Plastic Laminates*, ECN-C-91-003, May, 1991.

5. Mandell, J. F., Reed, R. M., and Samborsky, D.D., *Fatigue of Fiberglass Wind Turbine Blade Materials*, Contractor Report, Sandia National Laboratories, SAND92-7005, August 1992.

6. Mayer, R.M., *Design of Composite Structures Against Fatigue - Application to Wind Turbine Blades*, ISBN 0 85298 957 1, Antony Rowe Ltd., Great Britain, 1996.

7. Stroebel, T., Dechow C., and Zuteck, M.D. *"Design of an Advanced Wood Composite Rotor and Development of Wood Composite Blade Technology,"* DOE/NASA/0260-1, NASA CR-171713, GBI ER-11, December 1984.

8. *Germanischer Lloyd Rules and Regulations*, Part IV - Non-Marine Technology, Part 1 - Wind Energy, Regulation for the Certification of Wind Energy Conversion Systems, Chapters 4 and 5, 1993 Edition.

9. van Delft, D.R.V., and van Leeuwen, J.L. *"Full Scale Fatigue Testing of Wind Turbine Rotors", Presented at the IEA experts meeting "Wind Turbine Fatigue"*, April 1994, Petten, Netherlands.