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Theoretical and Practical Aspects of the Reliability Analysis of Timber Structures

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Summary

Structural reliability, expressed in terms of probability of failure or reliability index, is a useful tool for code calibration purposes. It is, however, important to bear in mind that the numerical results obtained are sensitive to input information like distribution functions. Without standardisation of this input data together with target reliability values, there is a great risk of misuse of the reliability analysis. Here a proposal is given for a standard format of code calibration.

Knowledge learned from failures shows that the reasons for structural failures are, in most cases, different from the information taken into account in the theoretical analysis. The reasons are gross human errors, which are beyond the scope of structural reliability analysis. Accordingly, the theoretical safety index only has a secondary effect on the frequency of structural failures.

1. Introduction

The use of structural reliability analysis in code calibration is an old topic, but it is alive in Europe because our building code system is gradually changing to a single European code (Eurocode) instead of several national codes. Even so, the safety level (specified safety-related factors) can be determined in each country separately. When doing so, national authorities have always been tempted to "improve safety" by increasing the safety margin. This is especially true in Finland, where several structures collapsed last year, and these cases were reported in the main media.

This paper is part of a discussion on appropriate target safety levels in timber construction. There are lot of published papers available on this topic. Unfortunately, it was not possible to make reference to these numerous papers, which really deserve it. This paper is mainly based on results published in [1].

Work in the area of learning from failures has intensified because of the recent failures. In the Nordic countries there are national efforts, which, hopefully, will work in close collaboration for our common benefit in the future.

2. Factors influencing code calibration

Code calibration refers to the use of structural reliability analysis for the determination of safety-related factors in structural codes so that they would be applicable to different materials, and equal levels of safety would be reached for different structures and loads. The use of limit state design, instead of allowable stresses, enables differentiation of partial safety factors for permanent and variable loads, and makes it possible to reach a more even nominal safety level in all structures. Here the influence of various input variables and target safety levels is discussed.

2.1 Target Reliability Level

Target reliability level is often expressed in terms of reliability index β. The Eurocode defines target β = 4.8 for a one-year return period, which is equivalent to 3.8 for a 50-year return period. This is for regular structures; other values are given if the consequences of collapse of the structure are especially high or low.

The Swedish building code defines three safety classes of buildings, and adopts target β values of 3.7, 4.3 and 4.8 for low, normal and high safety classes respectively. Consequently, the safety coefficient is multiplied by factors of 1, 1.1, and 1.2 respectively. In the new Danish building code a value as high as β = 4.79 is used as the target value for normal structures.

An international expert group, the Joint Committee on Structural Safety (JCSS), has worked on reliability-based design for years and suggests target values as listed in Table 1. The target β for normal structures is 4.2, and recommendations vary depending on what the cost of higher safety amounts to and what the consequences of failure are.

Table 1. Tentative target reliability indices β and associated target failure rates related to a reference period of 1 year and ultimate limit states [4]

Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Major consequences of failure
Large	3.1 (Pf ~ 10^{-3})	3.3 (Pf ~ 5 10^{-4})	3.7 (Pf ~ 10^{-4})
Normal	3.7 (Pf ~ 10^{-4})	**4.2 (Pf ~ 10^{-5})**	4.4 (Pf ~ 5 10^{-6})
Small	4.2 (Pf ~ 10^{-5})	4.4 (Pf ~ 5 10^{-6})	4.7 (Pf ~ 10^{-6})

When compared to failure information we can conclude that the target reliability level in all building codes is so high that the increase in the safety index only has a marginal effect on the real safety of buildings, if any. In a previous paper [3] it was analysed that an increase in the safety factor of timber structures by 10% in Finland 20 years ago would have caused at least a 200-times higher increase in building costs compared with the gain in less damages.

A high target reliability level also has disadvantages other than high building costs. The higher the target level, the more sensitive the result of code calibration is to the selection of parameters, and this can be used as a vehicle for unfair competition between materials. Because the parameters used in analysis are not known with great precision, it would be wiser to select less sensitive methods.

Finally, the reliability obtained in the analysis depends on the distribution of strength and loads. Initially, in the 1970s, load distributions were assumed to be Normal. When later, other distributions are used, the target β should be adjusted accordingly [2]. This does not seem to have been followed in the development of the Eurocodes and some national codes. Instead, for safety's sake, it seems to be easier to raise the nominal safety level than lower it. This has no effect on the safety of normal buildings, but it does increase building costs and influences the competition between building materials.

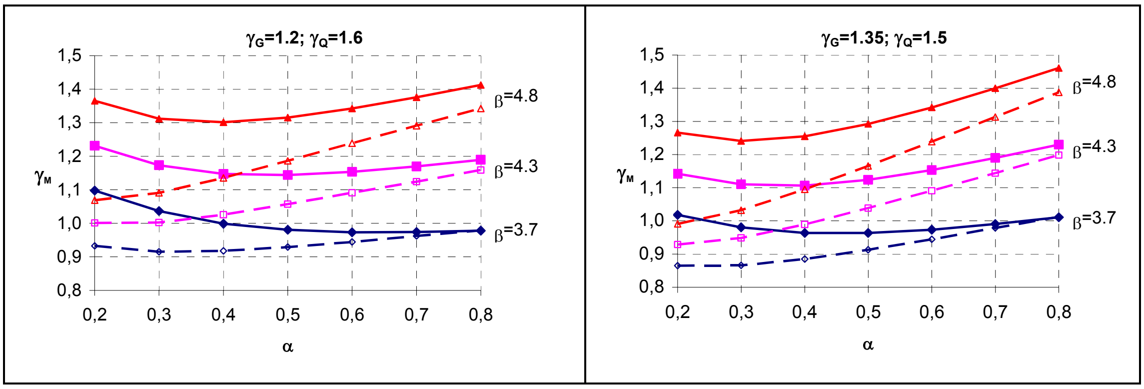

Fig. 1 Calculated γ_M values for three target safety index levels as a function of load ratio α. Solid curves are for COV of strength = 20% (lognormal) and broken lines for COV = 10%. Two sets of partial factors for load are used: γ_G = 1.2 and γ_Q =1.6 (left) and γ_G = 1.35 and γ_Q =1.5 (right). From [3]

2.2 Load Distributions

Load distributions were selected to be Normal when computers were not on the present level. In the Nordic countries the target value of β = 4.8 was adopted at that time, based on a Normal distribution of loads and lognormal distribution of resistance [2].

Later, it has been observed that natural loads (snow, wind) can be more accurately modelled by extreme distributions. Gumbel distribution has been adopted quite commonly. This has 2 consequences:

- Lower beta values are obtained for the same structures (4.0 vs. 4.8, see Fig.2).
- The result of analysis is less sensitive to the choice of parameters.

The latter fact is positive, because the input parameters are either not exactly known or their values are known to vary in the region where the result is applied. Based on this, the use of Gumbel distribution for live loads should be standardised, and, at the same time, the target safety index adjusted on a reasonable level.

Distribution of permanent load is commonly assumed to be Normal. The value and distribution of dead load only has a minor effect on the analysis of light-weight structures, as the timber structures are. This is a relevant question for heavy structures, and is not discussed here.

Selection of a reasonable target β value, the use of Gumbel distribution for live loads, and optimised selection of the ratio of partial factors for permanent and variable loads results in the pleasant situation that the same partial safety factor can be used for materials having COV of a strength not more than 0.20 based on lognormal distribution fitted to lower tail strength values. This would be true in a wide range of structures from heavy to light. This would suggest that practically same material safety factor can be used for steel, concrete and industrial wood products. Sawn timber graded to C30 and lower grades would require a higher material safety factor, say 1.4 vs. 1.2.

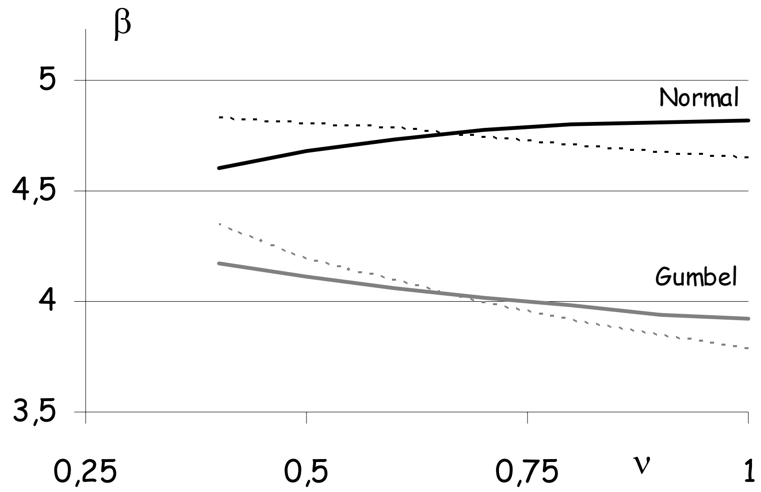

Fig.2. Reliability index levels calculated for the present Swedish code (continuous curves) and old code (dotted curves) when variable loads are Normal or Gumbel distributed. v is the ratio of variable load to total load. From [2]

2.3 Strength distributions

Quite commonly, lognormal distribution is used for the strength of building materials. This is found to be a good selection for man-made materials. For natural materials like sawn timber, Normal or Weibull distributions give a better fit, especially if the material is not strength graded. The grading procedure affects the distribution, depending on the quality of the grading, and the distributions may be different for different grades.

In spite of the exact form of distribution, lognormal distribution can also be used for sawn timber. The correct method of analysis requires that the parameters of lognormal distribution are based on fitting to the lower tail of test values, say 10 or 15 % of the weakest values. This should be done to obtain the correct result, because the lowest strength values have the greatest influence on the reliability value. A consequence of this is that the parameter of lognormal distribution indicating the coefficient of variation will normally be higher than the COV calculated from all the test results. However, the result of reliability calculation in terms of β by this method is as favourable for wood as one can obtain.

3. Proposal for selection of distributions and factors

Knowing that there are international bodies working with the standardisation of structural reliability analysis (JCSS, COST E24), here is a suggestion for timber structures to facilitate the discussion:

1. Variable loads: Gumbel distribution. If no regional information is available, COV = 0.4 should be used for snow and wind loads. COV = 0.2 can be used for floor loads.
2. Permanent loads: Normal distribution. COV = 0.05 or 0.1 gives the same practical result.
3. Strength: Lognormal distribution to be fitted to the lowest 15% of values (min. 75 values, total population 500).
4. Other factors, like model or dimension accuracy, can be taken as Normal distributions. In the case of sawn timber structures, these have a minor effect.

5. Target reliability level β = 4.0 is adequate with the selections above and would result in dimensions of structures similar to those we have in the Nordic countries today.

There are other factors, depending on load duration, moisture content and size of structural members, to be considered in the design of timber structures. Unless there is new and comprehensive information on these issues, they should be taken as deterministic factors according to the code of concern.

4. Relation of target reliability level to experienced failure cases

The target reliability level of building codes is generally so high that we can rarely find a failure case that is caused by statistical effects that have been taken into account in a structural reliability analysis [3]. However, we have structural failures annually. These failures are typically caused by reasons that are beyond the scope of statistical reliability analysis: cross-errors made by humans working in design, manufacturing or installation of structures. These errors are not acceptable and we have to counteract them by other means, like education, quality systems and inspection.

Nearly all recent structural failures of timber structures in Finland are covered by one or more of following reasons:

1. **Loss of stability**. Importance of stability of structural members is not understood by builders on site: compression members are not supported as required or racking resistance of the building is neglected. Design errors are not common.

2. **Moisture in wood**. Wood is wet for different reasons: leakage, vapour barrier lacking, rain during construction. Various problems result: rot, low compression strength, cracking.

3. **Inexperienced wood designer**. Failure mode of splitting of wood is forgotten. Weakness of wood in perpendicular to grain direction is not obvious to designers having basic education mainly in steel construction. Moisture loads can contribute to this failure mode by shrinkage.

5. Conclusions

The calibration of safety factors when building codes are renewed should be based on experience, which proves that the present dimensions of structures are adequate. This fact cannot be overruled by the occurrence of recent failures caused by cross-human errors, which cannot be counteracted by safety factors. Different methods are needed in the area of quality assurance of structural design and execution of construction work to achieve an acceptable quality of buildings.

References

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