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Model uncertainty in the assessment of transmission line towers subjected to cable rupture

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ABSTRACT

Model uncertainty affects all stages of structural reliability analysis, from the description of loads and the system itself to the process by which the effect of loads on the system is evaluated. The last issue has been largely ignored in the previous developments in the field, in part due to its elusive nature. A study conducted by CIGRÉ on transmission line (*TL*) towers subjected to static loads, among other exploratory assessments, demonstrated that mechanical model uncertainty was a relevant factor and could not be disregarded. The issue, in which attention is focused in this paper through the study of a specific problem, may significantly influence the outcome of reliability assessments. The dynamic response of latticed *TL* steel towers subjected to cable rupture is predicted by the use of various models with different degrees of sophistication or detailing. The predictions of the various models are compared with the aim of quantifying mechanical model uncertainty. In essence, the problem consists of evaluating the uncertainty in response predictions, once all parameters that define the external actions and the system itself have been unequivocally prescribed. Finally, possible ways to explicitly consider model uncertainty in reliability assessments and in code formulations are outlined.

1. Introduction

Model uncertainty pervades all stages of a structural reliability analysis, from the description of loads and the system itself, to the process by which the effect of loads on the system is evaluated. In this paper attention is focused on the last issue, which introduces uncertainty that has been largely ignored in structural reliability. In essence, the problem consists of evaluating the uncertainty in response predictions, once all parameters that define the external actions and the system itself have been unequivocally prescribed. Note at this point that the term is often used in connection with *statistical models*, for instance, in the choice or assessment of probability distribution functions (Ditlevsen and Madsen [1]), which in the opinion of the authors belongs in the area of *statistical uncertainty*. In this paper *model uncertainty* refers to the chapter of *epistemic uncertainty* concerned with the applicability, i.e. the prediction error, of a mathematical model adopted for the analysis of a perfectly known physical system. In the applications of the Finite Element Method in Structural Mechanics, for example, it includes not only practical aspects of the numerical solution, as the convergence of the results for a given mesh, but also the influence of element type and of the underlying mechanical theory.

In the specific case of transmission line (*TL*) structures, in which the loading is often time dependent, as for instance in the studies of turbulent wind action or sudden cable rupture, the mechanical model as well as the procedures employed in the dynamic analysis may significantly influence response predictions (displacements, member forces and stresses), justifying a study to quantify model uncertainty.

Several *TL* accidents that caused extensive structural damage occurred in recent years, as illustrated by serious accidents in Canada and France at the end of the decade, not described in the open literature, suggesting that efforts should be directed to a better understanding of the behavior of *TL* structures under dynamic loads. The applicability of the *equivalent static loads* recommended in design codes, including the loads due to cable rupture (ABNT-NBR 5422 [2]), should also be assessed.

In this context, the present paper aims at evaluating model uncertainty in the response of a *TL* tower subjected to the dynamic loads caused by sudden cable rupture. This is achieved by comparing the results of several mechanical models of a 138 kV double circuit self-supporting tower, from relatively simple models with a single tower subjected to a time-dependent load, expected to account for the effect of a cable rupture,

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to more complex models of an entire *TL* section that includes several towers, cables and insulator strings. The dynamic response is obtained by direct numerical integration of the equations of motion, using an explicit central finite differences scheme. The results of the various models are compared with response predictions determined using static equivalent loads, adopted in design codes. In addition, valuable data on model uncertainty was gathered, considering the influence of relevant factors such as cable model and boundary conditions.

By way of introduction, a brief overview of studies on model uncertainty in structural reliability is presented in Section 2. On account of their inherent differences, dynamic analyses are discussed separately in Section 3. The structural characteristics and design procedures of *TL* towers subjected to cable rupture are described in Section 4, while mechanical models and solution method are described in Section 5. Numerical examples are presented in Section 6. Finally, possible ways to explicitly consider mechanical model uncertainty in reliability assessments are outlined and the ensuing conclusions presented.

2. Model uncertainty in static problems

Static reliability problems are often posed in terms of a group of N random variables (RV) X_i, $i = 1, N$, that define the actions, the relevant properties of the system under consideration and a *limit state function* $g(X_i) = 0$ that divides the space into a safe region and a failure region. The limit state function is assumed to be a *known function* of the RV, in spite of the fact that it is generally the result of an approximate fit to experimental or numerical data. Very little evidence has been accumulated so far on the size of the errors involved in these approximations. Previous studies involving model uncertainty in static problems are briefly described next.

Soares [3] evaluates aspects of model uncertainty in the prediction of the buckling strength of steel plates employed in naval structures. On the assumption that the buckling strength of plates as well as their post-buckling behavior are governed by slenderness ratio (λ), initial imperfections, residual stresses, aspect ratio, type of loading and boundary conditions, several models were employed to determine the plate compressive strength. The total uncertainty was measured by the coefficient of variation of the experimentally determined plate strength (CV_R), which is attributed to the contributions of *physical uncertainty* and *mechanical model uncertainty*. The coefficient of variation that measured physical uncertainty (CV_F) is determined by Soares [3] by means of the FOSM—First Order Second Moment Method. The total coefficient of variation of a response quantity of interest was then determined by:

$$CV_R^2 = CV_F^2 + CV_M^2 \tag{2.1}$$

in which CV_M denotes the coefficient of variation associated with model uncertainty. Then, if the total uncertainty is obtained from experimental results, model uncertainty can be evaluated. Fig. 2.1 illustrates how physical and model uncertainties contribute to the total uncertainty for a range of values of slenderness ratio λ. It may be seen that for λ between 1.5 and 3.5, the coefficient of variation attributed to model uncertainty CV_M takes larger values than the coefficient of variation due to physical uncertainty CV_F.

CIGRÉ [4] undertook an ambitious project to evaluate the variability in the predicted response of *TL* steel towers, introduced by the mechanical model. Two towers were analyzed by twenty-seven engineering consulting firms of several countries. Each participant adopted a mechanical model to analyze the towers under a specified loading, in order to predict internal forces and strength of the previously selected members and also the towers' loading capacities. In view of the simplicity of the structure and its components, small variability of the results was expected. However, the predicted responses diverged considerably, as shown in Table 2.1. Prototype tests of the two towers were performed in a second stage, in order to measure the loads in the selected members, as well as the carrying capacity of the towers. The ratios between the predicted and measured values are shown in Table 2.2. The study clearly revealed that the model employed for analyzing a *TL* tower has a significant impact on its design and consequently can affect its reliability.

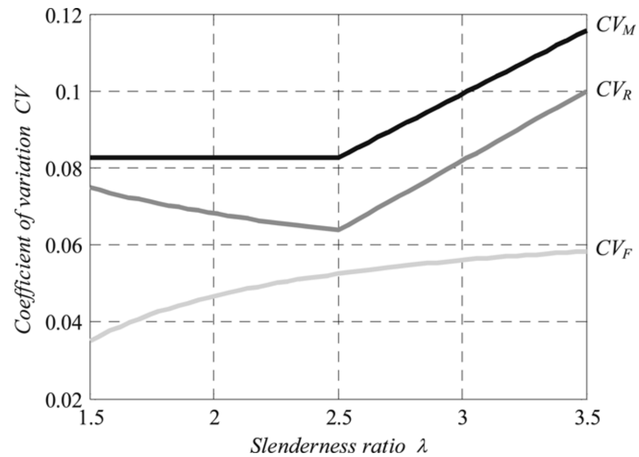

Fig. 2.1. Total uncertainty CV_R, model uncertainty CV_M and physical uncertainty CV_F in experimentally determined buckling strength of steel plates.

Table 2.1
Coefficients of variation of predicted response quantities (CIGRÉ [4])

	Tower 1			Tower 2		
	Smallest CV (%)	Largest CV (%)	Mean CV (%)	Smallest CV (%)	Largest CV (%)	Mean CV (%)
Forces in selected bars	4.4	22.0	10.7	1.2	42.4	8.8
Strength in selected bars	7.7	27.9	14.6	6.0	33.2	18.2
Carrying capacity of the towers	–	–	37.1	–	–	21.0

Table 2.2
Ratio between mean predicted values and measured values (CIGRÉ [4])

	Tower 1	Tower 2
Mean predicted load in selected bars/measured load	0.99 $CV = 10.2\%$	1.01 $CV = 32.8\%$
Mean predicted strength of the towers/measured strength	0.70	0.64

Menezes [5] presents an analytical and computational study to evaluate the influence of physical and model uncertainties in the reliability assessment of a *TL* steel tower, which was modeled considering the variability of boundary conditions, initial stresses and material properties. Stochastic finite elements are used in the evaluation of the response, allowing the consideration of the spatial variability and cross-correlation among the material mechanical properties, in addition to dimensional uncertainties. The results show that model uncertainty is a significant factor in the reliability assessment of the structure and should not be neglected.

Camargo [6] examines several aspects of mechanical model uncertainty in *TL* steel towers, such as the degree of internal redundancies, soil–structure interaction and slip at connections. Slippage at the joints is simulated through an axial stiffness reduction of some selected bars. Four self-supported towers were analyzed. In tests of tower subjected to differential foundations displacements, the measured member forces in important bars