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REVIEW

Similitude and scaling of large structural elements: Case study

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Abstract Scaled down models are widely used for experimental investigations of large structures due to the limitation in the capacities of testing facilities along with the expenses of the experimentation. The modeling accuracy depends upon the model material properties, fabrication accuracy and loading techniques. In the present work the Buckingham π theorem is used to develop the relations (i.e. geometry, loading and properties) between the model and a large structural element as that is present in the huge existing petroleum oil drilling rigs. The model is to be designed, loaded and treated according to a set of similitude requirements that relate the model to the large structural element. Three independent scale factors which represent three fundamental dimensions, namely mass, length and time need to be selected for designing the scaled down model. Numerical prediction of the stress distribution within the model and its elastic deformation under steady loading is to be made. The results are compared with those obtained from the full scale structure numerical computations. The effect of scaled down model size and material on the accuracy of the modeling technique is thoroughly examined.

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1. Introduction

Any new design is subjected to many investigations through theoretical analyses and experimental verification. As a system becomes more complex, assumptions are usually made in order to formulate a mathematical model for the system. In the absence of a complete design base, a new system requires extensive experimental evaluation until it gains the necessary reliability and desired performance. For large and "oversize" systems, such as offshore/onshore rigs, tall buildings, dams, bridges, spacecraft, airplanes, and space stations, creating the actual working conditions for testing the prototype most of the time is impossible, as in providing a zero gravitational acceleration condition on the ground for testing large space stations or antennas [8,16,4].

Even when a prototype test is possible, it is expensive, time consuming, and difficult to control. Thus, it is extremely useful if a prototype can be replaced by a similar scale model which is much easier to work with. The only possible way to obtain experimental data of overall performance of such a system and the interaction of its elements is to design a small similar system (scale *model*) which replicates the behavior of the actual system (prototype). The accuracy of the behavior of the prototype, which is predicted from interpreting the test results of the model, is dependent on the relationship between the corresponding variables and parameters of model and its prototype [3].

Similarity of systems requires that the relevant system parameters are identical and these systems are governed by unique set of characteristic equations. Thus, if a relation or equation of variables is written for a system, it is valid for all systems which are similar to it [16,7]. Each variable in a model is proportional to the corresponding variable of the prototype. In establishing similarity conditions between the model and prototype two procedures can be used. The similarity conditions can be established either directly from the field equations of the system or, if it is a new phenomenon and the mathematical model of the system is not available, through dimensional analysis. In the second case, all of the variables and parameters which affect the behavior of the system must be known. By using dimensional analysis, an incomplete form of the characteristic equation of the system can be formulated [4]. This equation is in terms of non-dimensional products of variables and parameters of the system. Then, similarity conditions can be established on the basis of this equation.

2. Theories of scale model similitude

Similitude theory is concerned with establishing necessary and sufficient conditions of similarity between two phenomena. Establishing similarity between systems helps to predict the behavior of a system from the results of investigating other systems which have already been investigated or can be investigated more easily than the original system. The behavior of a physical system depends on many parameters, i.e. geometry, material behavior, dynamic response, and energy characteristic of the system. The nature of any system can be modeled mathematically in terms of its variables and parameters [15].

A prototype and its scale model are two different systems with different parameters. The necessary and sufficient conditions of similitude between prototype and its scale model require that the mathematical model of the scale model can be transformed to that of the prototype by a bi-unique mapping or vice versa [14]. Qian et al. [10] studied the scaling laws for impact damage in fiber composites by experiments. Their experiments on scale plates, made of carbon and subjected to impact loads, were carried out and the scaling laws for scaling (up) the strain responses of the specimens to those of the full-size ones were derived. The results show that the derived scaling laws could reasonably predict the responses of the undamaged carbon plates undergoing impact loads. Simitses et al. [13] studied the design of scale-down models for predicting the laminated shell buckling and free vibration. In their article, the similitude theory is employed to establish the similarity between the chosen structural systems, and then the scaling laws are derived and used to predict the physical characteristics of the full-size structures. Vassalos [17] investigated the physical modeling and similitude of marine structures and provided some valuable information concerning the appropriate use of models in the design of marine structures. Safoniuk et al. [11] presented a method to scale up the three-phase fluidized beds, in which the scaling laws are obtained by achieving geometric and dynamic similitude with the aid of the Buckingham π theorem. Chouchaoui et al. [2] used the similitude theory to develop the scaling laws for predicting the elastic behavior of a laminated cylindrical tube under tension, torsion, bending, internal and external pressure from the corresponding ones of the scale model.

2.1. Scaling laws and parameters optimization methods

Several techniques were introduced where most of the literature uses a gradient-based optimization method and the solution often oscillates or diverges, depending upon the initial search point, since the model and the measurement errors can make the objective function complex [1,5]. One of the approaches used to overcome this problem is to use a robust optimization method and genetic algorithms (GAs) which were successfully used to find the parameter set in a stable manner. Nevertheless, this stability of convergence is achieved only at the expense of efficiency. Taking the advantage of the