SLang - the Structural Language

Solving Nonlinear and Stochastic Problems in Structural Mechanics

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1. Introduction

Recent developments in structural mechanics indicate an increasing need of numerical methods to deal with stochasticity. This process started with the modeling of loading uncertainties. More recently, also system uncertainty, such as physical or geometrical imperfections are modeled in probabilistic terms. Clearly, this task requires close connection of structural modeling with probabilistic modeling.
Nonlinear effects are essential for a realistic description of the structural behavior. Since modern structural analysis relies quite heavily on the Finite Element Method, it seems to be quite reasonable to base stochastic structural analysis on this method. Commercially available software packages based on the Finite Element method (e.g. ANSYS (1992), ABAQUS, (1989)) are able to cover deterministic structural analysis in a very wide range. However, the applicability of these packages to stochastic problems is rather limited. On the other hand, there is a number of highly specialized programs for probabilistic or reliability problems which can be used only in connection with rather simplistic structural models as e.g. PROBAN (Madsen, 1988), STRUREL (Gollwitzer et al., 1994), ISPUD (Bourgund and Bucher, 1986). In principle, there is the possibility to combine both kinds of software in order to perform a reliability analysis for realistic structures. For many practical applications the definition of data transfer between the programs shows up to be a major difficult task.
In order to circumvent these problems, the software package SLang (**S**tructural **Lang**uage) has been developed. SLang basically represents a command interpreter which acts on a set of relatively complex commands which communicate via input and output data structures such as scalars, vectors and matrices.
After a brief summary of software requirements and strategies of implementation the paper shows two applications of the SLang program to structural engineering problems which deal with stochasticity in combination with geometrical and physical nonlinearities

2. Software Requirements

Software for probability-based engineering decision making needs to satisfy certain requirements. The tools to meet these needs have to be based on the state-of-the-art in both structural analysis and stochastic modeling. In brief they can be itemized as follows:

a) Nonlinear Finite Element modeling
b) Static and dynamic structural analysis
c) Randomly spatially distributed structural properties
d) Randomly distributed loads in space and time
e) Monte Carlo Simulation technology

f) Capability to determine reliability measures

Here the first two items traditionally belong to the domain to FE-codes, whereas the remaining items are covered by special probabilistic codes. However, from a computational point of view it is virtually impossible to separate e.g. items (a) and (c). The same is true for items (b) and (d). As a consequence, it appears that any useful software package must be able to integrate the above mentioned items smoothly. This is related mainly to the data transfer between the components of the code.
For many reliability based applications multiple, repetitive structural analysis under varying loading and/or systems conditions are required. In these repetitions, the variations usually cannot be pre-determined, but have to be based on previous results. An example is advanced Monte Carlo Simulation (e.g. Adaptive Sampling, Bucher 1988) where the sampling strategy is adapted to the results of previous samples. Applying such a strategy requires that the FE-code can be driven by the probabilistic code. However, the probabilistic code needs to interpret the results from the FE-analysis as well in order to act appropriately.
These steps have to be made transparent to the user, since in many cases the stochastic analysis of nonlinear structures is not a simple task to be solved in a "black-box". The user must have the possibility of following each step of the analysis and must be able to interact if necessary.

3. Implementation of the Software

Following a long tradition in software development for advanced structural engineering applications, it seems useful to formulate tasks in small, easily controllable steps (e.g. Krätzig et al., 1977). These steps should be combined into large segments which can be executed repeatedly. Such a solution is achieved by implementing a programming language in which the individual commands pertain to stochastic and structural analysis. The requirements for such a problem-oriented language were formulated by Schuëller and Bucher, 1994. The implementation in the form of SLang is shown by Bucher et al., 1995. SLang integrates Finite Elements with stochastic modeling at a level which appears to be sufficient for a wide range of engineering problems. In addition, several advanced graphics features allow the visualization to computational results in a way suitable for the decision making process.

Fig 1: SLang-User interface

In brief, features of SLang include:
a) Geometrically and materially nonlinear beam, shell and solid elements.
b) Iterative and incremental static and dynamic analysis
c) Random field modeling of material properties and geometrical data
d) Step-by-step user control with direct access to intermediate results
e) Multiple user-definable graphics windows with animation capability
f) High-quality PostScript graphics
g) Sound output of digital data

Fig.1 presents the user-interface of the SLang program. Users are able to create an unlimited number of windows where results of an ungoing computation may be visualized. The flow of execution can be controlled interactively using the SLang-bar. This is a dialog box with several pushbuttons associated with the execution status. While most commands being processed are read from a pre-edited text file, interactive commands may be entered any time through the SLang-bar. This is most helpful for debugging complex processes such as in nonlinear stochastic analysis.

4. Applications to Stochastic Structural Problems

The following two examples represent applications of the SLang program to problems with a high degree of interaction between the stochastic and structural data. Both applications require solution techniques for nonlinear system behavior.

4.1. Stadium Roof Under Stochastic Wind Load

The analysis of structures due to wind loading is commonly based on quasi static load assumptions. Dynamical loads due to fluctuations in wind velocities are usually considered in terms of static loads with appropriate magnification factors. This example shows a more realistic approach for a model representing the roof of a stadium which is submitted to dead load and stochastic wind loading (Zabel 1996). The three dimensional structure which mainly consists of prestressed cables and a diaphragm is discretized with geometrical nonlinear cable and shell elements, see Fig. 2.

Fig 2: Stadium Roof under Dead Load, Prestress and Mean Wind Loading

The force flux of the structure acts in this case in a comparable manner as a spoke wheel. The "hub" consists of two prestressed inner tension rings, the "rim" represents an outer compression ring idealized as stiff within the model. In radial direction pairs of prestressed cables represent kind of "spokes" between the inner tension and the outer compression rings. The diaphragm has mass but neglectible stiffness contribution. This computer simulation of the structural behavior requires a finite element formulation able to capture large displacements and possibilities to define the prestress conditions. The final shape of the structure is actually determined by the amount of pre-stressing.
The loading of the structure consists of dead load and dynamic wind load. The wind load itself acts as a surface load on the diaphragm and may be split into a static mean and a stochastically fluctuating part. To account for the spatial correlation of the stochastic wind velocity the diaphragm is discretized into sectors. Within these sectors the wind velocities are modeled as Gaussian stochastic processes in time with a determined gust spectrum (Davenport, 1961). The different processes of the discrete sectors follow a spatial correlation model (Kristensen et al., 1981). The Monte Carlo simulation of time series of the fluctuating wind velocities then serves to determine the fluctuating surface loads in a straightforward manner.
The calculation of the response function requires a linearization of the governing equations of motion at the state defined by dead load, prestress conditions and mean wind loading. Due to the strong nonlinear behavior of the prestressed cables, this static calculation was performed as a dynamic relaxation problem with assumed high damping rations. The response in terms of displacements and forces is then obtained by application of a modal superposition technique.
A comparison of the extreme values of cable forces obtained with a calculation where quasi static loading conditions are assumed, clearly shows the considerable conservativity of conventional calculation procedure.

4.2. Buckling of Shell Structures with Random Geometrical Imperfections

The investigation of the stability behavior of structures is of crucial importance for the designing engineer. Commonly the structures analyzed are considered as *perfect* in material and geometry. Yet it is well known that already small geometrical imperfections often strongly influence the stability behavior of structures. These geometrical imperfections, which arise during the construction of the structure, are usually of stochastic nature. In current design codes these effects are considered with empirical knock down factors. If detailed Finite Element calculations are performed usually only some imperfection shapes stemming from the experience of the designing engineer are taken into account. Obviously the geometrical imperfections directly influence the reliability of the structure. With current design models these reliability considerations are simply neglected.
The following example (Schorling 1996) shows a direct approach to this class of problem. An imperfect stringer stiffened shell (see fig. 3) is analysed with respect to its reliability towards buckling failure. The structural model consists of shell and beam elements. Both element types are geometrically nonlinear, the beam elements take into account the eccentricity of the stringers. The restraint and loading conditions are idealized as deterministic.
The geometrical imperfections are interpreted as randomly spatially distributed fluctuations with respect to a perfect structure. They are modeled mathematically as spatially correlated Gaussian random fields which act on the nodes of the structural model. The correlation model takes into account different correlation functions in circumferential and longitudinal direction of the shell as well as deterministic locations of the restrained and the loaded nodes. The statistical moments for the imperfection amplitudes and the parameters of the correlation functions are determined from detailed measurements of geometrical imperfections performed for this structure in the early 70th

(Arbocz and Abramovich 1979). The standard deviation of the imperfections amplitudes was determined to be 30% of the shell thickness of 0.19mm.

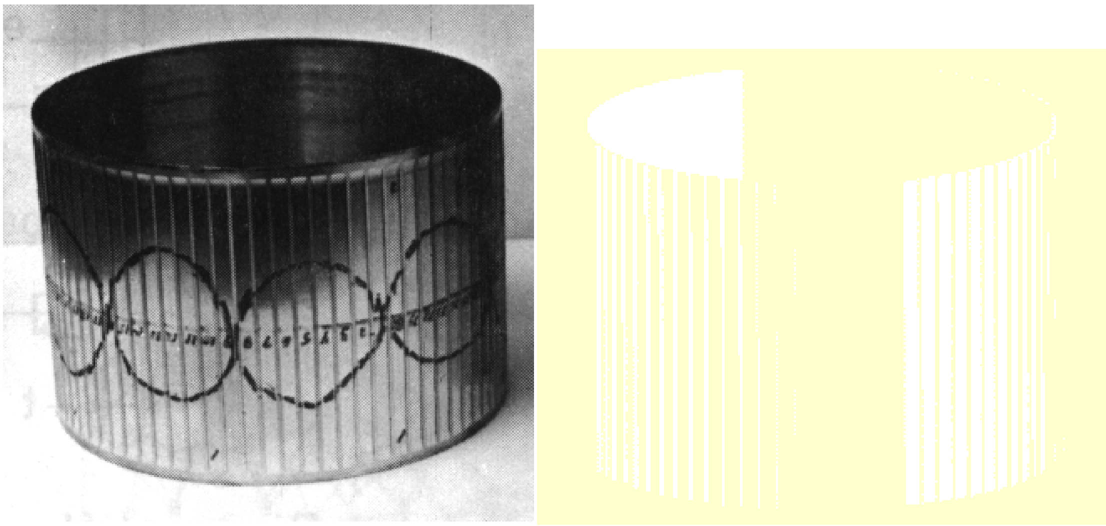

Fig 3 Stringer Stiffened Shell Structure (Arbocz and Abramovich 1979) and FE model

The nonlinear buckling loads are determined by a method based on indifference criteria. This requires the expansion of the stiffness matrix into an asymptotic series with respect to the load parameter. Quadratic terms of the asymptotic series have been taken into account. This corresponds to the calculation of the buckling load by solving a quadratic eigenvalue problem. The method as presented enables to determine the buckling load of the perfect shell almost accurately, for imperfect shells the procedure represents an improved approximation compared to a linear buckling analysis. Concerning the numerical effort this method shows up to be much less cost intensive as e.g. procedures which are based on path tracing methods.
The probability of failure as a functions of the load parameter is estimated by performing statistics on 250 buckling loads of realizations of imperfect shells derived by Monte Carlo simulation. Fig 4. shows the dependencies between load factor and probability of failure in logarithmic scale. The buckling load of the perfect shell and the experimental buckling load as derived by Arbocz and Abramovich 1979 are indicated in Fig. 4.

Fig 4 Results of Monte Carlo Simulation

Even though a sufficiently large number of experimental buckling loads with identical structural properties for comparison with the numerical results is not available, the numerical results demonstrate the significant decrease in the buckling load for the simulated imperfect shells.

Concluding Remarks

SLang is being developed as a numerical tool for the analysis of stochastic problems in structural mechanics. The software concept relies on well-established methods of structural and probabilistic analysis. The applications show that SLang is able to cover a fairly wide range of problems. Future developments should aim at enhancing numerical efficiency which plays a crucial role in all Monte-Carlo-based stochastic methods.

References

ABAQUS, User´s Manual, Version 4.8, Karlson & Sorensen Inc., Rhode Island, 1989

ANSYS, User´s Manual, Revision 5.0, Swanson Analysis Systems Inc., 1992

Arbocz J., Abramovich H. : The Imperfection Data Bank at the Delft University of Technology-Part1, Delft University of Technology, Department of Aerospace Engineering, Delft, 1979

Bourgund, U. and Bucher, C.G.: "Importance sampling procedure using design points - ISPUD - a user's manual", Report 8-86, Institute of Engineering Mechanics, University of Innsbruck, Austria, 1986.

Bucher, C.: "Adaptive Sampling - An Iterative Fast Monte Carlo Procedure", Struct. Safety, Vol.5, No.2, June 1988, pp 119 - 126.

Bucher, C., Schorling, Y., Wall, W.: "SLang - the Structural Language, a tool for computational stochastic structural analysis", Proc., 10th ASCE Eng.Mech.Conf, Boulder, CO, May 21-24, 1995, pp 1132 - 1126.

Bucher, C. and Schuëller, G.I.: "Software for Reliability Based Analysis", Structural Safety 16 (1994), pp 13 - 22.

Gollwitzer, S., Zverev A., Cuntze, R., Grimmelt M., Structural reliability applications in aerospace engineering, Proc. ICOSSAR'93, August 9-13, 1993, Innsbruck, Austria, A.A. Balkema Publ., Rotterdam, pp 1265 - 1272.

Krätzig, W.B, Metz, H., Schmid, G., Weber, B.: "MISS-SMIS, Ein Matrizeninterpretationssystem der Strukturmechanik für Praxis, Forschung und Lehre, Mitteilung Nr. 77-5, Institut für Konstruktiven Ingenieurbau, Ruhr-Universität Bochum, 1977.

Madsen, H.O.: "PROBAN: Theoretical Manual for External Release", Technical Report No 88-2005, AS Veritas, Oslo, Norway, January 1988.

Kristensen, L., Panofsky, H.A., Smith, D.: "Lateral Coherence of Longitudinal Wind Components in Strong Winds", Boundary Layer Meteorology 21, 1981, pp 199 - 205.

Schorling, Y.,: "Beitrag zur Stabilitätsuntersuchung von Strukturen mit räumlich korrelierten geometrischen Imperfektionen ", eingereicht als Dissertation, Bauhaus Universität Weimar, 1996

Zabel, V.: "Untersuchung eines leichten, flächigen zugbeanspruchten Tragwerkes unter dynamischer Windeinwirkung am Bespiel einer Stadionüberdachung", Diplomarbeit, HAB Weimar -Universität, 1996.