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Educational and Professional Implications of Reliability Assesment in Computerized Structural Analysis

Conséquences, sur l'éducation et la profesion, de la détermination de la fiabilité dans le dimensionnement de structures à l'aide de l'ordinateur

Einfluss der Zuverlâssigkeits-Schâtzung bei Computerberechnung von Tragwerken auf die Ausbildung und die Berufstâtigkeit

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Summary

The continuing growth of computerized structural analysis and its increasing impact on engineering practice raise the problem of assessing and improving the reliability of its results. Some aspects of this problem are briefly discussed here, precisely: verification and qualification of structural software; certification of program users and enhancement of their professional standars through various types of educational processes.

Résumé

Le développement continu du dimensionnement de structures à l'aide de l'ordinateur et son influence grandissante sur la profession d' ingénieur soulève le problème de la détermination et de l'amélioration de la fiabilité des résultats. Quelques aspects de cette question sont traités, et en particulier la vérification du logiciel applicable aux structures, la qualification des utilisateurs des programmes et l'élévation de leur niveau professionnel au moyen de divers types de formation théorique et pratique.

Zusammenfassung

Die dauernde Entwicklung der Computerberechnung von Tragwerken und deren steigenden Einfluss auf den Ingenieurberuf wirft das Problem der Zuverlässigkeits-Schätzung und Verbesserung von Resultaten auf. Einige Aspekte dieses Problems werden kurz dargestellt, insbesondere: Prüfung und Beurteilung der Qualität von Programmen. Qualifikation des Programmbenützers und Verbesserung des Berufsniveaus durch verschiedene Arten von Ausbildung.

1. INTRODUCTION

In the last two decades the cost of computer use has been reduced by a factor of ten roughly every five years and such a trend is likely to continue in the near future, along with further developments in computer technology. This circumstance provides sufficient reasons for surmising that computerized analysis will play in engineering of tomorrow even a more important role than it does nowadays. In particular, nonlinear and transient structural problems, until recently almost prohibitive, will be solved routinely in years that lie ahead. The results of such analyses are generally difficult to be interpreted and checked on the basis of engineering judgement and intuition, which are hardly illuminating in the presence of complex or unusual mechanical behaviors; on the other hand, a large number of decisions is bound to be based on results supplied by computers. In view of these facts and prospects, there are grounds to be concerned about the responsible use of computers for structural engineering purposes.

Clearly, there cannot be such thing as absolute reliability assessment of the results of a complex computerized analysis. Errors may be due to bugs in the software, to failures in the hardware, or to inappropriate use of both.Particularly in front of problems which are intractable by hand calculations and hardly accessible to intuition, a combination of inadequate computational tools and inexperienced users may lead to a situation which is undesirable and dangerous.

The scope of this paper is to discuss the actions which could be taken in order to raise the level of confidence of computerized stress analysis.

The narrowest range of possible actions concerns the "verification" of computer programs, i.e. checking that a program is actually capable to do with satisfactory accuracy the calculations for which it was designed. A more ambitious task, referred to here as "qualification",is to ascertain whether the mathematical model adopted as a basis for the analysis represents a sufficiently close description of the mechanical system in the engineering situation considered. However, reliability of computerized structural analysis can be established only by an integrated process which encompasses verification, qualification of computer programs and, finally, a critical appraisal of results, which will be referred to here as "validation".

Even more difficult and perhaps inherently elusive, appears to be any action aiming at an assessment of users' competence, and possibly at its formal certification .

Attention is paid herein primarily to measures apt to enhance the professional standards in the community of structural software users. This discussion, covering both continuing education and normal engineering curricula, inevitably leads to the institutions potentially active in this area and responsible for gathering and registering the results of assessments of merit, both of software and users.

2. VERIFICATION OF STRUCTURAL SOFTWARE

Verification means checking that computer programs do exactly what they are supposed to do. This is a difficult task,as programs for structural analysis may be comprised of several hundred thousands of FORTRAN statements and may be used following a large number of different computational procedures. Moreover, verification includes checking correctness and completeness of the program documentation as well. Programs are seldom documented adequately, in part because documentation is generally regarded as a tedious and distasteful chore to be done at the end of the job. Programming or documentation errors may be detected after many years of satisfactory use.In fact, particular applications may require unusual solution paths,array dimensions never used in earlier applications or non-standard mesh arrangements,thus leading to situations unforeseen by the program developer. Moreover,many kinds of errors produce a limited perturbation of the results and remain undetected until a skillful user faces an application which magnifies their consequences.

It can be said, therefore, that there is no such a thing as absolute verification. On the other hand,a thorough testing would be harodly possible, and in most cases useless, because computer programs become rapidly obsolete due to advances in hardware technology and computational mechanics. Note that the simple addition of a new capability may inadvertently damage existing well-tested procedures. These and other reasons explain why the certification of computer programs was never attempted, although widely discussed since years, [1] .

In spite of all the above circumstances, verification of computer programs can be successfully carried out provided its scope be limited merely to generate an acceptable level of confidence. By this wording we mean that the uncertainties due to programming errors may be reduced to the same incidence level as those caused by hardware malfunctioning or mistakes in the design ad/or construction process.

An important step toward safer computer programs is the adoption of a modern programming style that can be called "programming for debugging". The first generation of finite element computer programs has required average debugging costs as high as fifty percent of the total cost of developing an operational program 2 . Therefore it makes sense to plan a debugging strategy in the early stages of designing a new computer program. Being easy to debug should become one of the fundamental requirements of future computer software. Practical implications follow at two different levels.

At the software architecture level, a clear decomposition of the algorithm into functional modules must be sought. The purpose is to make visible the function of each module and the transfer of information. The concept of completely modular structure leads from the usual large general-purpose software systems to the so-called programming systems. The latter are simply a comprehensive set of software modules and data handling tools that can be combined in a very flexible way as needed by each particular application. Since each module can be debugged independently and new features can be added by means of separate modules, the overall software reliability is generally increased by an order of magnitude [2] . The cost of debugging is much reduced because the implications of a single program segment can be understood without taking into account remote parts of the program.

At the level of coding the various modules, "programming for debugging" means that a substantial effort should be spent in making the FORTRAN code readable. In particular, marginal computational benefits should be sacrified in favor of the linearity of the algorithm.

Guidelines for advanced and safe computer programming have been done by many authors and would not be pertinent to this Colloquium. However existing contributions to software engineering are dispersed in the literature and hardly available to many engineers-programmers responsible for the production of structural analysis codes. Since there are no established channels for teaching it, computer programming for structural engineering can still be regarded more as an art than as a science. The importance of this remark should be appreciated in view of current trends of computerized structural analysis.

Due to the increasing availability of less and less expensive and more and more powerful computers, of structural packages and of information on structural analysis techniques, an increasing number of users may try to develop their own proprietary packages. The result may be a mushrooming of poorly tested and highly unreliable software systems. Appropriate actions have to be taken by educational institutions and professional bodies in order to avoid unacceptable consequences. In this respect it would be useful to establish and make available comprehensive sets of test problems, particularly for nonlinear and dynamic analysis. Program developers should be required to demonstrate successful solution of these benchmark problems before any stress report based on their program can be taken into consideration.

Clearly, the solution of a limited number of benchmark problems is not a substitute for the program verification and may engender a false level of confidence. However, the combination of better programming techniques and of a broad range of test problems certainly provides a significant level of verification.

3. QUALIFICATION OF ANALYSIS PROCEDURES AND VALIDATION OF COMPUTER RESULTS

The analysis of engineering structures rests on assumptions concerning the behaviour of the materials, the structure geometry, the nature of the applied loading and other aspects of physical systems. In any specific application, the use of a computer program is meaningful only provided the underlying assumptions (say for instance: linear elasticity) are shown to be acceptable. When design procedures rely heavily on the computer, the analyst may be induced to make assumptions which are difficult to check. For instance, non-axisymmetric bodies may be modelled axisymmetric in order to reduce the size of the problem. Analogously, significant details may be omitted in order to simplify the mathematical model. Even more difficulties are encountered in nonlinear problems. For instance, stress-strain curves derived from standard uniaxial tests may not be adequate for large strain elastic-plastic analysis. In fact, the assumed stress-strain curves are only averages over the specimen; on the other hand, they must be generalized to multiaxial constitutive laws through suitable hypotheses. Similarly in the presence of geometrical nonlinearities it is possible to perform a bifurcation buckling analysis. However, the practical meaning of the computed bifurcation load is difficult to ascertain unless a much more complex investigation on the imperfection sensitivity of the structure is performed as well [9].

The above remarks show that qualification of analysis procedures is not a simple task. However, there are areas where appropriate actions could and should be taken, in order to increase the reliability of computerised structural analysis.

E.g. in some applications the significance of geometric nonlinearities is difficult to estimate in advance. However it is possible to compute first the linear solution and then have an "a-posteriori" estimate of the magnitude of the nonlinear terms. Computer programs for geometrically nonlinear analysis should be able to furnish this information routively, whenever possible.

A second example concerns nonlinear material behavior. Many programs have a capability for elastic-plastic analysis. However the models of material nonlinearity available in the program may not be appropriate for important areas of application (for instance soils). In the preceding section the need for a comprehensive set of test problems has been pointed out. This set should encompass a wide range of fully solved elastic-plastic benchmark problems, especially devised for verifying the range of applicability and the level of accuracy of the material models available in the program.

Verification of the computer program and qualification of the solution procedure are not sufficient for verifying the consistency and accuracy of the computed results. We will call"validation"the set of checks usually performed "a posteriori" to this scope. There are at least four possible causes of concern. The most impredictable one is certainly malfunctioning of hardware: this may be due,e.g., to faulty integrated circuitry or to errors in the data transmission from a remote computer to the user's terminal. The second cause of concern is the possibility of undetected input errors. A good computer program contains checks of the consistency of the input data and of other quantities computed during the solution process (for instance,non negative diagonal stiffness coefficients). It seems worth encouraging systematic comparison of the efficiency of the diagnostic capabilities in large scale computer programs currently in use. This kind of investigations(though, unfortunately, not appealing to the academic environment) would likely represent a major contribution to safer computerised structural analysis, inasmuch it would stimulate the development of more advanced data checking techniques.

The third cause of concern stems from initial truncation or round-off errors. Nowadays this is not a very common cause of failure, because large computers have a large number of digits. However, the use of minicomputers spreading in small civil engineering design offices,is likely to modify rapidly the situation. E.g. large differences between axial and bending stiffness of frameworks are a common cause of ill-conditioning, which is usually diagnosticated by checking equilibrium at nodes. Program developers who do not automatically provide this check,should be censured. When more complex structures are considered, the diagnostic of ill-conditioning is much more difficult. The computation of the conditioning number is not widely adopted as it is relatively expensive and occasionally very conservative. The fourth and final cause of concern are discretization errors. Particularly in nonlinear ad for three-dimensional problems,the user is forced to limit the number of degrees, of freedom to avoid prohibitive costs. It is usually stated that discretization errors can be controlled by mesh refinement. This is certainly true in two-dimensional problems, although many users prefer to adopt from the very beginning a conservatively large degrees-of-freedom number in order to avoid a second computation and the attendant delays. On the other hand, mesh refinement of 3-D problems is difficult to apply because of its overwhelming cost.

The above remarks show that control of discretization and numerical error is often based on engineering intuition only. Algorithms for providing automated error control are currently being developed at ISMES [3] . Preliminary but fairly extensive numerical results have been successful. If the possibility of inexpensive "a-posteriori" error controls will be confirmed,it is likely that future computer programs will make use routinely of this new approach.

As a conclusion, validation of computerized structural analyses requires expertise in structural mechanics, numerical analysis and software engineering. This suggests that it might be more appropriate to qualify the user besides the solution method.

In the absence of user's qualification procedures, the solution of complex analysis problems should be checked by a separate computation performed by an objective outside organization. This is already standard practice in the shipping industry.

4. CERTIFICATION OF SOFTWARE USERS

The user of structural software seldom coincides with the program developer, whose competence is indirectly checked by the program verification, or with the engineer, who is responsible for the outcome of the overall design process. The program user has to be responsible for the validity and the accuracy of the calculations he carries out. This responsability may often be legally attributed to a computer service bureau; however,the professional competence of individuals represents the crucial factor anyway. The stress analyst using computers as a normal working tool, is generally required both to know thoroughly the solution methods implemented in his programs,and to have a deep understanding of the physical theories on which those methods rest. Not only is he supposed to be familiar with the use of his programs and computing facilities,but also he needs an integrated knowledge of numerical analysis, programming techniques and structural mechanics, in order to fully exploit his software capabilities and possibly to modify and,occasionally, to further develop his computer codes.

How to check, certificate and enhance the user's competence in the above areas, is a problem which cannot be discussed without due consideration to the environment, both technical and social. In fact, any effective solution to such a problem necessarily involves a variety of ingredients and factors, some of which loosely connected with the sofware users themselves: the analyst's employers, the customers who pay for the structural analysis or design, governmental agencies in charge of technical supervision and control, software producers, hardware suppliers, professional societies, universities, and finally, to some extent, even the general public.

As far as the environment is concerned, it appears useful, for concreteness and clarity, to refer here exclusively to two distinct national situations. One situation, examplified nowaday by the USA, is characterized by a leading role in technology, a large amount of activities in the specific field, a multeplicity of the above listed organizations, all acting under the pressure of strong competition, in a society with much mobility of manpower and readiness to changes and adjustments. The other reference situation (Italy might be cited as an example) is characterized by still limited, though growing, computerized stress analysis activities and specialist community, little adaptive educational institutions and governmental agencies, professional associations with marginal roles, a centralized and stratified society where traditions, stable aggregations of individual interests and pressing social problems affect the policy making processes in technical areas.

We believe that only in the former environment the professional ethics and competence of structural software users can be guaranteed through formal certification. In fact, an effective licensing program based on (possibly periodical) exams and registration, presumes a strong motivation and an active role on the part of at least three entities: the community of those whose professional status is being certified and, hence, protected; an institution apt to responsibly carry out the whole process in the general interest (preferably an engineering professional association); some legislative body capable to provide the legal framework. An official licensing system (parallel to the Professional Engineer Registration in use since decades) was recently advocated and debated repeatedly in the USA, [1 , 4] ; although still a controversial, issue, as far as we know, the trend is towards the implementation of licensing in a near future.

The aforementioned, far-reaching implications of a reliable certifying process makes it impractical, in the writers' opinion, for environments of the latter type, whereas insufficient information prevent the authors from expressing opinions on other kinds of situations, e.g. in Soviet Union.

5. IMPROVING PROFESSIONAL STANDARDS OF USERS

The environmental conditions which affect the prospect of certification and licensing programs, act in a similar fashion on the potential role of formal university education in enhancing the general competence of structural software users. Although slowness of changes is everywere claimed to be a permanent attitude of academic institutions, a variety of independent and diversified engineering schools, competing with each other and actively interacting with the outside world, is clearly a factor in favor of prompt curricula adjustments to emerging needs. Infact, in the former (say American) situation depicted in the preceding section, structural engineering curricula have been significantly reshaped, so that e.g. courses on programming and computer methods, finite element analysis, applied approximation theory, have become normal offerings in most Departments. Moreover, in view of the future growth of large-scale computerized analysis in such sophisticated areas as non-linear, transient or interdisciplinary problems, the prospects have been envisaged [5] of 7-8 years doctoral curricula without research connotation and special academic institutes for computer applications.

In the latter, less responsive environment mentioned in Sec.4, contributions from formal education to the improvement of stress analysts' competence are bound to be limited and delayed, but by no means negligeable. The reasons and possible remedies cannot be discussed here, for space limitations; some hints and details can be found in [6] [7] .

Very significant contributions to the same purpose, almost independently from environmental conditions, can be provided by continuing education. Training practitioners in new methodologies and disciplines, or updating and "brushing up" their technical and scientific bachgrounds, are educational processes obviously needed in times of rapidly expanding technology and underlying sciences. But the remarkable impetus recently gained in most countries by engineering continuing education and its tremendous potentialities can be explained by its peculiar features, like the following ones (see e.g. [8]): flexibility of contents and teaching methods, due to the extra-curriculum, informal nature of short courses; compatibility of these with professional committments of participants; self-financing; use of new teaching aids, such us videocassettes and CRT's for dissemination of carefully designed courses in the engineering environment; relatively easy interchange of lecturers, experience and documentation at the international level; natural involvement with mutual motivation of universities, research institutes, professional societies, design offices, industries, government agencies.

A measure of the potentialities of continuing education in the stress analysis profession, can be achieved e.g. by considering the important role played by short courses in spreading a knowledge of the finite element method among practitioners, most of which left university before it was formally tought.

At least two peculiar aspects of continuing education for structural software users appear worth mention here. The English wording "I hear, I forget; I see, I remember; I do, I understand" is especially suitable in our context; the implication is that workshops (and the facilities involved) have to be a substancial ingredient of continuing education for software users. The second aspect is related to the difficult issue of users certification: the easiest solution, in all professional and social environments, might consist of a formalized system of granting continuing education credits, based on "ad hoc" designed programs of coordinated and qualified short courses.

6. CONCLUSIONS

In view of its growing impact on engineering practice, computerized structural analysis has been considered herein from the standpoint of possible improvements of its confidence level. Practical prospects of progresses in this direction have been critically examined and found fairly promising.
Some of them (verification, qualification, validation) are of technical nature and concern primarily the structural software. Other kinds of initiatives(licensing, restructuring formal curricula, continuing education) are addressed to the users, have broader and somewhat controversial implications, and may be most beneficial in the long range.

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