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GRADUATE STUDIES IN PLASTIC ANALYSIS AND DESIGN

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1. INTRODUCTION

The previous speakers in this symposium on plastic design and its relation to education have shown why the engineering profession has a genuine interest in plastic design and, as a consequence, that industry will need men who are trained in this technique. It has also been suggested to you that opportunity is available to universities to incorporate the basic fundamentals into the undergraduate curriculum.

How, then, may graduate studies in plastic design assist in meeting our long-range educational and industrial needs? The broad answer is to be found in examining the function of a university and of its graduate program. You will all agree that the function of a university is to teach. At Lehigh we believe that the educational responsibilities of a true university go beyond this and that they include extending our knowledge, through research, and the dissemination of this knowledge, for the good of mankind.(1) Even in the graduate research program we believe that our prime function is to train the graduate student to take a responsible place in society as a teacher, a research worker in industry, or as a practicing engineer. Since a considerable number of our graduate students eventually go into university work, "training for teaching" is an important function.

In this context, and with respect to plastic design in particular, the aim of a graduate program will first be to train the student and, second, to extend knowledge through research. At Lehigh the training program in plastic analysis and design has included:

(a) Formal classes in which the fundamentals and the methods of plastic analysis are taught.

(b) Special individual courses in which the student carries out independent studies.

(c) The MS and PhD thesis program.

(d) Research assistantships in which the student carries prime responsibility for a research study.

To be sure, the research assistantship (item d) is not a requisite to teaching plastic design to graduate students. But certain problems remain to be solved, and by participating in the research a graduate student gains just that much more insight into the plastic behavior of structures.

For those of you who may be interested in the research aspect, the new work will go on to extend the applicability of plastic design to structural types not now covered, and further research should improve the presently recommended plastic design procedures. The aim of such research is to promote the greatest possible economy in the use of our engineering materials through the use of design methods that are rational and simple.

In commenting on the general philosophy and objectives upon which a graduate program should be built, the best recommendations are those contained in your own manual on graduate study in engineering:(3)

> "There are important differences between undergraduate and graduate students, but the difference is more one of developing personal responsibility and of the implied need for scrutinizing evidence than one of overal objectives....
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> "Graduate work should be highly individualized and the student should be put more and more on his own responsibility until finally he has a more profound idea of what is meant by accuracy of statement and learns to judge with humility."

Bacon has written what might be called "The Graduate Student's Proverb":(3)

> "Read not to contradict and confute, nor to believe and take for granted, nor to talk and discourse, but to weigh and consider. Some books are to be tasted, others to be swallowed, and some few to be chewed and digested. Reading maketh a full man, conference a ready man, and writing an exact man."

Naturally this applies to any program of graduate work; but it bears repeating.

In most schools the undergraduate program is fairly crowded and a considerable period of time must elapse before a new course may be offered in lieu of one already "established". On the other hand, the graduate program is generally not fixed and the curriculum is free to expand. It does mean that teachers with an interest in plastic design must be available. In offering the 1955 summer course "Plastic Design in Structural Steel", (and in which the American Society for Engineering Education kindly cooperated) it was our hope that teachers would be stimulated to study further into the subject and begin to present the material to their students. We have been gratified to learn, since then, that at least twenty such courses were started.

A second need is for qualified graduate students and research assistants. The challenge is directly to you who teach undergraduate students! Those who are qualified to enter graduate school should be encouraged to do so and should be told of the opportunities for research employment which will enable them to continue their studies.

By way of historical background, such work as has been done at universities in the past on plastic design has been done in the graduate curriculum. Studies at Lehigh commenced in 1946 through research assistantships established by the AISC and the Welding Research

Council. Both at Lehigh and elsewhere, some of the basic concepts must have been a part of the graduate curriculum for some time because these principles are a part of advanced textbooks (see Refs. 4 and 5). The earliest recorded notes on the flexure of beams beyond the elastic limit are by St. Venant in 1864 (see p. 366 of Ref. 4). Ewing's 1899 textbook also discussed plastic bending (see p. 4 of Ref. 8). The first conscious use made of the method was by Kazinczy in the 1920's.(2) The amazing thing is that we are just now beginning to apply the plastic methods to structural design. This is probably due to the fact that adequate experimental confirmation was not available and systematized procedures had not yet been developed as an aid to the designer. It remained for the universities to do this work and the task has largely been completed as a part of the graduate programs at Cambridge (England), Brown University, and Lehigh.

At Lehigh University the first formal course (a seminar with three students and 1 listener) was held in the summer of 1949 under Bruce Johnston. In this instance the objective of training teachers was apparently successful because all four are still in university work (two at Lehigh, one at New York University, and one at the University of Texas).

It is the purpose of the remainder of this discussion to outline what a graduate program can offer in the field of plastic design. The discussion is limited to our experience at Lehigh University, but perhaps it will serve to stimulate your critical discussion. As a supplement to these remarks, Prof. J. F. Baker has prepared a paper entitled, "Teaching the Plastic Theory of Structures" for presentation at their Symposium in September, 1956 (Cambridge University, England)

and has kindly consented to a presentation of the essence of his thoughts on the subject.

2. A GRADUATE PROGRAM

As already noted, the four aspects of our graduate instruction in plastic design have been the formal course, the individual study course, the MS and PhD thesis program, and the research assistantship. Chronologically they developed in the reverse order, but future programs would normally follow the given sequence. The first two aspects are essential; the research is supplementary.

1. Formal Course in Plastic Analysis and Design

Both the seminar type of course and the formal lecture type have been used. In the former the instructor gives a preliminary lecture or two on the fundamental concepts of plastic analysis and the later lectures (usually in the form of reviews of the most recent literature) are given by the students.

At Lehigh, the first lecture-type course for graduate students on the subject of plastic analysis and design was given in the spring of 1954, was repeated this year, and it is planned to offer it each year for the immediate future. Generally speaking it is divided into four parts, (the percentage of time spent on each part being shown):

Fundamental concepts	--	20%
Methods of Analysis	--	24%
Additional Considerations	--	36%
Design	--	20%

The course content is indicated in Table 1.

Table 1

Outline of a Course in Plastic Analysis and Design

FUNDAMENTAL CONCEPTS

- Stress-strain relationship
- Conventional vs. plastic design
- Flexure of beams (moment-curvature relationship)
- Method of virtual displacements
- Theorems of ultimate strength

METHODS OF ANALYSIS

- Mechanism method
- Equilibrium method
- Method of Inequalities
- Examples
- Plasticity check

ADDITIONAL CONSIDERATIONS (modifications, limitations,etc.)

- Axial force
- Shear
- Local, lateral, and column buckling
- Repeated loading
- Deflections
- Rotation Capacity

DESIGN

- Connections and design details
- Factor of Safety
- Rules of Design
- Design Examples

The fact that but 20% of the time in the course has been given to design problems and design examples reflects the emphasis that we believe should be placed on learning the "why" instead of the "how", particularly in the graduate curriculum.

With regard to text material as a teaching aid in plastic design, no complete textbooks are yet available, although a number are known to be in preparation. A considerable portion of the subject matter

of the material contained in Table 1 was presented in a set of lecture notes for the "summer course".[7] A monumental review of the outstanding work done by Baker and his colleagues at Cambridge University has been published within the past two months.[8] Van den Broek's "Theory of Limit Design"[9] presented some fundamental ideas about plastic theory, and texts by Timoshenko[4] and Hoff[6] contain more than casual treatment of plastic analysis of beams and structures.

No special course problems that involve experimental work are included in the above, since such studies are a part of the work now to be described.

2. Individual Study Courses

Courses in which the student carries on an individual structural research project have been a feature of the graduate program at Fritz Laboratory for years. Such studies may be entirely analytical or may involve a combination of analysis and testing. Even when testing is desirable, the facilities available at most universities should be adequate to meet ordinary needs. The individual study course provides an excellent opportunity for the student to develop research ability. Reports should be required as a means of training the student.

3. Thesis Program

The MS and PhD thesis program works hand in hand with the research assistantship (see below) as a training medium. Because of the intensive effort involved, the thesis program tends towards a more complete training of the student ("writing maketh an exact man"), and is more likely to produce more promising research results.....at least this has been our experience in the plastic design work. Of the 21 published papers resulting from the project, three have been the direct result of PhD thesis work.

4. Research Assistantship

We come now to probably the most important aspect of our graduate program for training and research in the plastic behavior of structures. It is the research assistantship. Here industry and government have cooperated with the universities in a very real way by sponsoring research programs. Our particular thanks go to the American Institute of Steel Construction, Welding Research Council and Navy Department who have sponsored research on plastic design.

At the Fritz Laboratory, under the supervision of members of the staff, research assistants take responsible charge of an investigation, carrying out theoretical studies, planning test set-ups where required, conducting any necessary experiments, and writing reports for eventual publication. While the functions of the assistantship tends to be more clearly allied with research, an excellent opportunity exists for the student to develop individual responsibility, to work and think independently, and to plan and organize.

Opportunities for graduate research programs are by no means restricted to those that involve large scale experiments. As stated earlier, much can be done with testing facilities that are ordinarily available at universities. Further, since the assumptions of plastic theory as applied to the design of rigid frames in steel have been verified experimentally, analytical studies become more important. These may include:

(a) Application of plastic analysis to the design of structural types other than those considered to date.

(b) Comparative design studies.

(c) Simplification of procedures necessary to account for possible modifications of plastic theory.

(d) Improvement in techniques for analysis and design.

Thus, much valuable analytical work may be done without the need for test facilities.

3. SUMMARY

In summary, then, an effective program of graduate studies may be given which consists of a formal course supplemented by individual research courses. The formal course should stress the fundamental principles upon which the design procedures are based and should treat in detail the additional considerations necessary to assure proper performance of a structure designed by the plastic methods. The individual study course provides opportunity for the student to carry out a program of his own with but a modest amount of supervision.

Although it is by no means required, the training program is enhanced if research assistantships or fellowships may be arranged. When necessary, modest test facilities will often be adequate.

These graduate studies will assist in meeting our long-range educational and industrial needs primarily by teaching the fundamentals of the theory to those who, in most cases, will later be in a teaching position or who, through their own research, will extend our knowledge of the plastic behavior of structures.

To carry out such a program,universities must have qualified graduate students with an enthusiasm for advanced studies. It should be a challenge to you to thus encourage your best students. Incidentally, at least 75% of our research in this field has been done by foreign

students. There are simply not enough qualified Americans available to meet the demand.

Certainly all of the future training will not be in the graduate curriculum. An equal challenge for all who are interested in this subject is to work with those responsible for the undergraduate curriculum to see that the more important fundamentals are taught there. Whether we recognize it or not, plastic design is moving out of the ivory tower. Already, more than just a few structures have been built in England according to designs based on the plastic method. Consequently students at engineering colleges must learn the principles that will enable them to use this implement now added to the engineer's toplbox of design methods.

Or maybe the tool was there all the time. Certainly our ancestors, without a knowledge of stress analysis, had to base their "designs" on the maximum load-carrying capacity; and to our knowledge one man did use the method successfully in the 1920's. Graduate studies showed that the tool was dependable (through experimental verification of theory) and suggested ways in which the tool could best be used (through developing methods of analysis and systematized design guides).

According to the American Iron and Steel Institute we are celebrating the centennial of steel. At least in the next hundred years we won't be wasting the material we threw away during the first hundred by ignoring the unique property of steel -- that of ductility in the plastic range.

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