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Design Work by Engineering Undergraduates at Cambridge

J. B. DWIGHT,
M A, M SC, A M I MECH E, A M I STRUCT E
B. D. THRELFALL, M A, A M I C E
ENGINEERING DEPARTMENT, UNIVERSITY OF CAMBRIDGE

This paper introduces the structural design work carried out by engineering undergraduates at Cambridge University. A short history of previous courses is followed by a description of the problems set and of a typical design course in action. A variety of typical designs is discussed and an assessment made of the value of such courses.

Introduction

At Cambridge, as at most places, an undergraduate reading engineering receives a diet which consists largely of analysis. Given something that already exists, he is taught how to predict its performance. With the large number of topics to be covered, such an approach is inevitable and, indeed, desirable. No university can hope to turn a schoolboy into an engineer; its job is to equip him with good analytical tools that will help him to grow into an engineer after he has gone down.

At the same time, no one nowadays would defend a purely analytical curriculum. It is vital to keep telling undergraduates that engineering is an art as well as a science. There are too many bright young men who think that life is composed of differential equations and computers, and that a rigorous mathematical solution can be found to any technical problem. Such men take a long time to develop into useful engineers, and what should be some of their most creative years are often misused.

It is up to the engineering schools to stop this happening, by providing exercises which bring home the difficulties in applying idealised theoretical methods to practical problems. A common practice is to set drawing office design work in the specialised field of engineering which the man is studying. Thus a civil engineering student might be given building or bridge structures to design, while his mechanical counterpart would undertake various pieces of machine design. Such work is valuable, and at its best can be a stimulating experience. One of the authors can remember, as an undergraduate who was more steeped in theory than most, the awakening effect of being made to design a sewage pump to pass 7in. diameter spheres.

But there is a danger with such exercises that the designs produced will simply be inferior copies of current practice, and serve only to blunt any critical or inventive ability which may be there. The effect is to give pre-conceived ideas of how things should be made.

At Cambridge we have developed a different type of design exercise. Before describing this it must be pointed out that our engineering degree course (Mechanical Sciences Tripos) is a general one, embracing all the main branches of engineering, which aims to educate rather than provide professional training. That comes later. We try to produce men who will be capable of producing novel solutions in novel situations.

The essential feature of our design exercises is the Design-Build-Test principle, coupled with a competitive atmosphere. The men are grouped into small classes and work in pairs. Each pair designs a small structure to a given specification and then builds it. After costing, the finished structures are, one by one, tested to destruction with the whole class watching. The winning design is the cheapest one to reach the required collapse load.

Various problems are employed, all of which are entirely artificial and not intended to represent real designs. The general method of construction is laid down, but apart from this the men have complete freedom in choosing a suitable overall configuration to satisfy the requirements. They are thus subjected to a realistic design situation, in which they must investigate possible solutions, decide which one to adopt, analyse it and then work out the details. At the same time, the problems are simple enough to be undertaken with relatively little theoretical knowledge, and are such that the structures can be built by the men themselves without the need for appreciable manual skill. Great care is taken to ensure that during the design stage no man has access to previously completed structures to the same specification, and is thus free of any pre-conceived ideas.

Design work on these lines figures mainly in the work of first and second year men, and counts as a section of the regular programme of laboratory work. Some architectural students also take part. Two main forms of construction are used:

FIRST YEAR: Truss-type structures in light-gauge angle (steel or aluminium) with pop-riveted joints.

SECOND YEAR: Spot-welded sheet metal fabrications.

Typical structures are 3ft. long and weigh from 3 to 15lb. Some 200 have been built in the last three years. The testing of these has been highly educational, for staff as well as students.

A similar type of exercise, but in model concrete, is offered to third year men.

These exercises are seen to be similar to the interesting projects described by Dr. Zorowski of North Carolina State University at the 1964 Conference[1]. The main difference would appear to be that ours are lengthier exercises than his, involving more calculation and relying less on intuitive judgment. At present all our problems are of a structural nature, but next year some mechanical problems will be started, still on the Design-Build-Test principle.

History

The first design project of this type at Cambridge was introduced in 1954 by a colleague, Mr. S. L. Harris, and was offered as an optional laboratory experiment to third year men. The problem was a 5ft. span structure resembling a gantry girder. Originally the construction was in Mecanno angle, but this was later changed to light-gauge angle folded up in our own work-shops, as this was cheaper. Each structure was designed and built by a team of six, who had first to test the material and obtain their own experimental strut data before they could start designing.

This project was immensely successful and continued for nearly 10 years. The head of the department, Professor Sir John Baker, decided that work of this nature should be introduced more widely, and in 1962 the authors were given the job of implementing this decision. A pilot-course was run during the 1962–63 session, manned by 12 enthusiastic volunteers from the second year, on whom a variety of problems was tried out. Much valuable experience was gained from this, and enabled optional design courses to be offered to the first and second year Normal Course* men during the two following sessions (1963–64 and 1964–65). A total of some 200 men took part during these two years.

The procedure was very similar to that now adopted, with the men working in groups of two. It was found too time-consuming to make them do their own material testing, and they were asked to take on trust values provided.

There were two variations from present practice. One was that each structure was built by a different group from that which had designed it. This had the virtue of ensuring a reasonable clarity of draughtsmenship if the final structure was to resemble the intended design. It was, however, found to be an unfair procedure in many cases, since a group who had designed a neat simple structure might find themselves spending undue time building to someone else's far more complex design. Further, a good design might be penalised in the test by having been shoddily made by another group. For these reasons this practice has now been dropped, and each group build their own structure.

The other difference from current procedure was that the designs were assessed on weight only. In each class the winners were the group who had produced the lightest successful design. This led some groups to devise excessively complex structures, just to save weight, regardless of labour content. The costing system now introduced has largely overcome this difficulty, and is helping to reduce the time spent in fabrication.

In the current session (1965–66) such a design exercise has been made a compulsory item for the first year (Normal Course), who total about 100. It is still optional for the second year (Normal Course), of whom about 50 have elected to take part. Some 40 architects are also participating. The organisation has become more stream-lined in the light of experience, and only the most satisfactory problems have been retained.

The model concrete project, which follows the technique evolved by Brock[2], has been offered as an optional exercise for the third year men (Normal Course) last year and this, and is taken by about 10 to 15 men per year.

Problems

(1) PROBLEM TYPES

The first consideration, when selecting problems, must be whether the undergraduates are capable of tackling them at the theoretical stage they have reached. For a first year man in his first term, this precludes almost everything except simple tension and compression—in other words, a truss-type problem. With this in mind, the three problems in Fig. 1 were chosen for the first year men, to be given to successive classes in the order shown. These are intended to produce "truss" type structures.

Second year men, having had at least a full year of structural theory, are equipped to attack a more complex problem; for them, the two problems in Fig. 2 have been used, to be solved in a "plate girder" fashion.

There is need for more than one problem for each course to avoid the possibility of a group seeing the solutions of a previous group to the same problem; it is most important that there should not be preconceived ideas at this stage. As at present organised, it is possible for two groups to do each problem.

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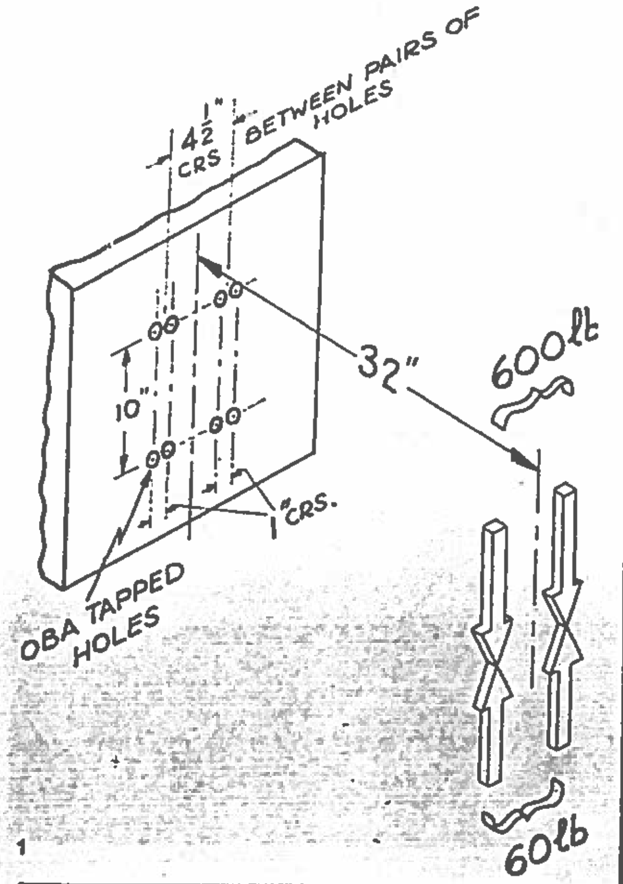
*The "Normal Course" are the men who spend three years reading for their Part I (a general course covering all main branches of engineering science and sufficient for an honours degree). The "Fast Course", who take Part I in two years, can do design work of a conventional kind during their third year while working for their Part II (More advanced study in a selected field of engineering).



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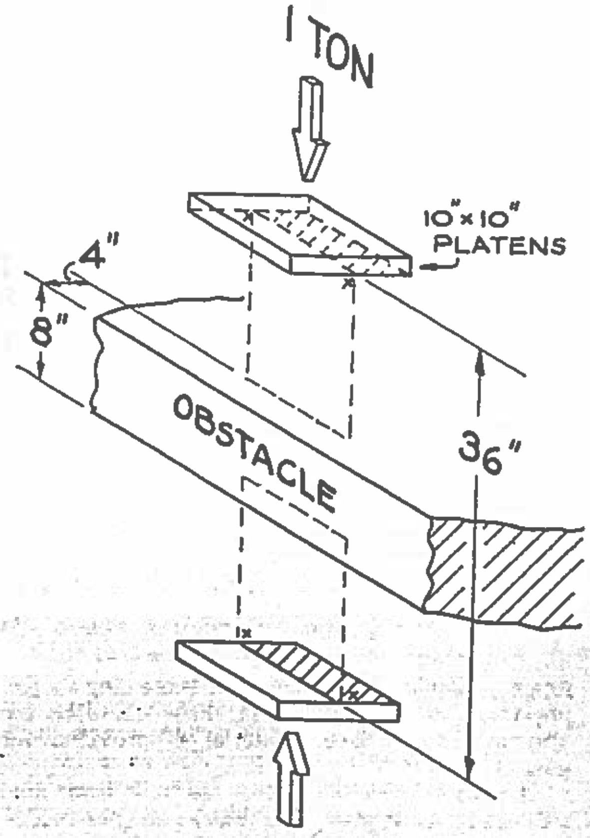

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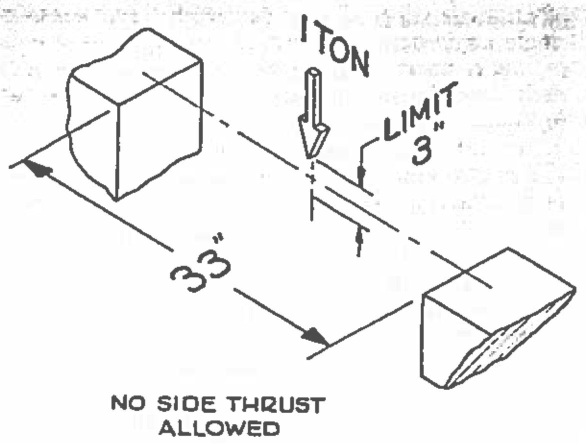

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Fig. 1—FIRST YEAR PROBLEMS: Truss-type construction, using light angle (steel or aluminium) joined with pop-rivets. Loads shown are collapse loads.

(1) 32 in. cantilever. Load applied equally at two points by spreader provided.

(2) 33 in. span girder. Central point load applied through a shackle.

(3) 36 in. cranked column. Structure may only touch platens to right of points X and must pass to left of obstacle.

In presenting both types of problem, stress has been laid on compliance with the "site conditions"; structures which, while carrying the design load, do not fit the test rigs are disqualified, though still tested.

(2) MATERIALS

The choice of materials is limited by what is readily available, by what can be easily worked with simple tools, and by the need to be able to give sufficient design data to enable a reasonably meaningful design calculation to be made.

From these considerations, mild steel and medium strength aluminium alloy (H30–WP) have been selected as the best materials to use.

For the first year problems a supply of light gauge angle is provided, in one or other of these metals. In each case a range of 7 sizes is available, the steel angles having been folded up from sheet in 3ft. lengths, and the aluminium ones obtained from outside in the form of extrusions†. The steel angles range in size from ⅜in. × ⅜in. × 0.022in. to ¾in. × ¾in. × 0.048in. The aluminium size

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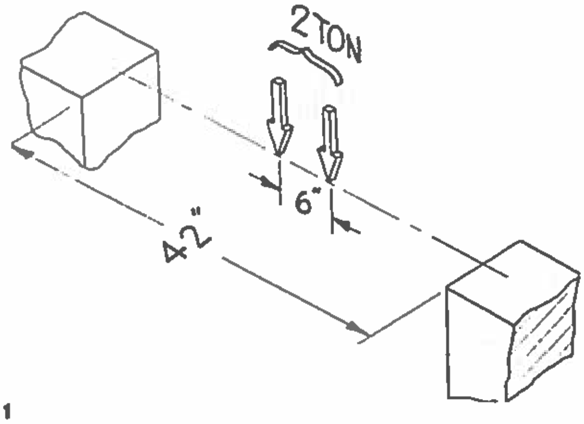
†Aluminium material in use at present has been kindly provided by the Aluminium Federation.



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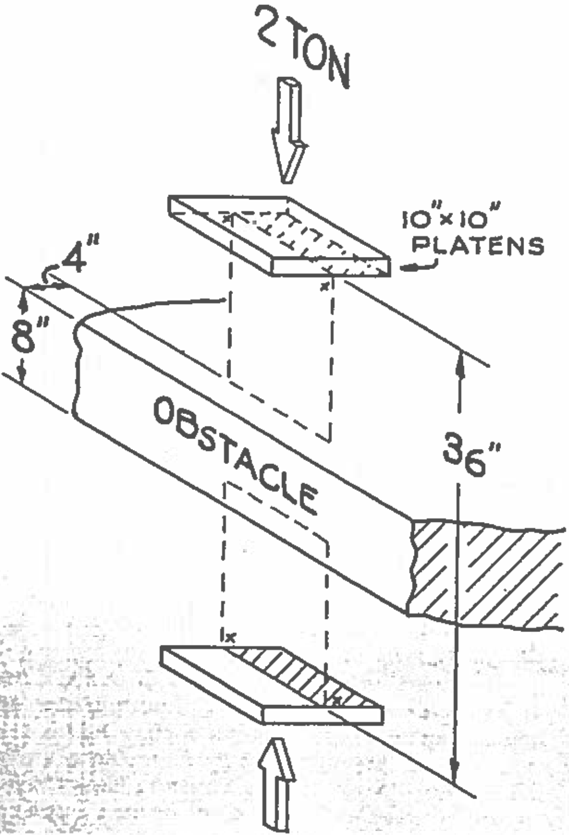

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Fig. 2—SECOND YEAR PROBLEMS: Folded sheet-metal construction, using steel sheet joined with spot-welds. Loads shown are collapse loads.
(*1*) *42 in. span beam. Load applied equally at two points on top of beam by spreader provided.*
(2) *36 in. cranked column. Structure may only touch platens to right of points X and must pass to left of obstacle.*

range is similar. For jointing these angles ⅛in. pop-rivets are normally used; B.A. size bolts are also available. Sheet material is provided for gussets.

The second year structures are built from mild steel sheet, using guillotine, folder and spot-welder. Standard 8ft. by 4ft. sheets are supplied, in even gauges from 16 SWG (0.064in.) down to 24 SWG (0.022in.). Joints are normally spot-welded, which is very quick, but rivets and bolts are also provided (at a price) for joints that cannot be got at with the spot-welder.

The properties of the steel sheets are variable, some having a yield stress of only 12 tonf/in^2, some being as high as 17 tonf/in^2; however, a value of 14 tonf/in^2 has been found a practical one for design purposes. The aluminium material used (H30-WP) has a guaranteed 0.2% proof stress of 16.5 tonf/in^2.

(3) DATA

Having regard to the limited theoretical knowledge of the undergraduates at first year level, and to the aim throughout these courses of persuading the partakers to think rather than rely on formulae, the data provided are of the simplest. The yield (or proof) stress of the material in tension, the main criterion, is given, together with the associated yield stress in shear. This fundamental stress applies, of course, also in compression, but the idea of buckling, not yet dealt with in lectures, must be introduced. To avoid difficulties, very simplified strut curves are provided, giving buckling stress plotted against L/b, where b is the breadth of an angle's leg. These deal with three cases—a single angle bending about its weakest axis, a pair of angles their weaker way, and a pair of angles their stronger way. Figures are supplied for shear in rivets, shear and tension in bolts, and bearing in the various thicknesses of plate.

For the second year problems, where the participants have a greater structural awareness and knowledge, the type of problem dictates a different approach. By now the men have had basic beam theory in lectures; they should be able to calculate the stresses in a proposed design with some precision, and compare them with the yield strength of the metal. More complex stability problems arise, such as local buckling of the individual plate components. The men have to assess these factors to some extent by feel and intuition, although simple empirical formulae are provided to help them assess local buckling strength. (Real life designers are in no better position!) They are also given some idea of the strength of spot-welds, although this is rather a variable quantity.

For each course, the data supplied, in the form of a printed handout, contains a statement of the problem, a list of the material available, a strut

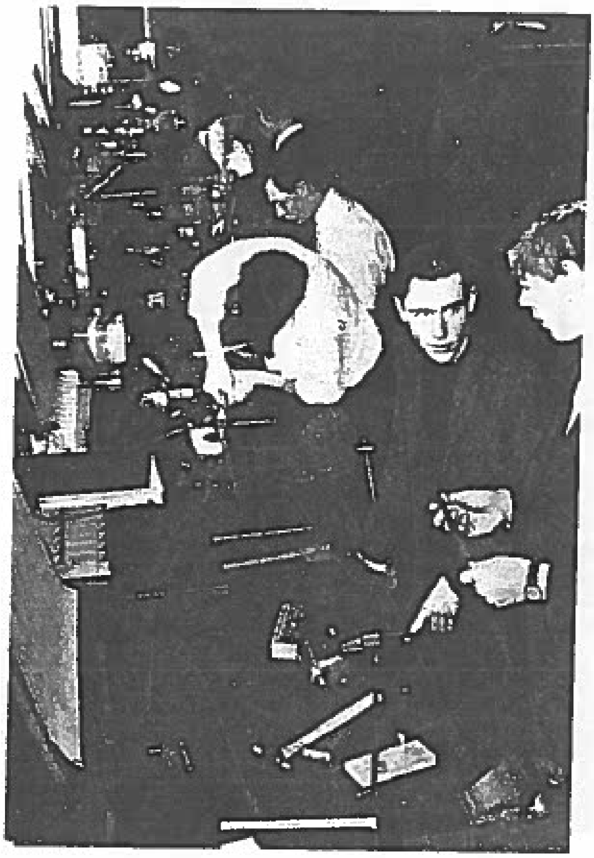


Fig. 3—MANUFACTURE: A first year class in the workshop making truss-type structures for Problem No. 2. The variety of tools can be seen, including pop-riveting pliers.

curve where applicable, and a summary of the course.

(4) TEST RIGS

The testing arrangements for both first and second year courses are so arranged that failure of a specimen is obvious, but as far as possible not catastrophic. To this end, hydraulic systems are used.

For the first year, the system is in the form of two identical hydraulic jacks, one loading the specimen, one a load cell, both in the same circuit as a single pump. The designers can test their own structure by operating the pump; failure is clear when the needle of the dial gauge in the load cell drops back, and loading can at once be stopped. In some cases, it is even possible to rescue the structure, repair it and retest.

A much larger hydraulic testing machine is used for the second year structure, a 100-ton machine on its lowest (5 ton) range. Here the maximum load reached can be read from a slave pointer, left behind when the machine pointer falls back.

In both cases, the undergraduates are shown the test rigs before they start designing, and know precisely how the load is to be applied—though this does not prevent some of them from designing structures which cannot be loaded by the given means.

The Course in Action

To try to make a dry description come alive, a typical course is followed through all its stages of designing, drawing, fabricating, costing, testing and report writing. For this purpose a first year course has been chosen: and some of the snags arising are brought out.

The second year course is similar, but the class are left more to their own devices, being free to contact the demonstrator if they need him. However, they are still required to keep to the deadline dates—and, being volunteers, are on the whole as keen.

(1) DESIGN AND DRAW

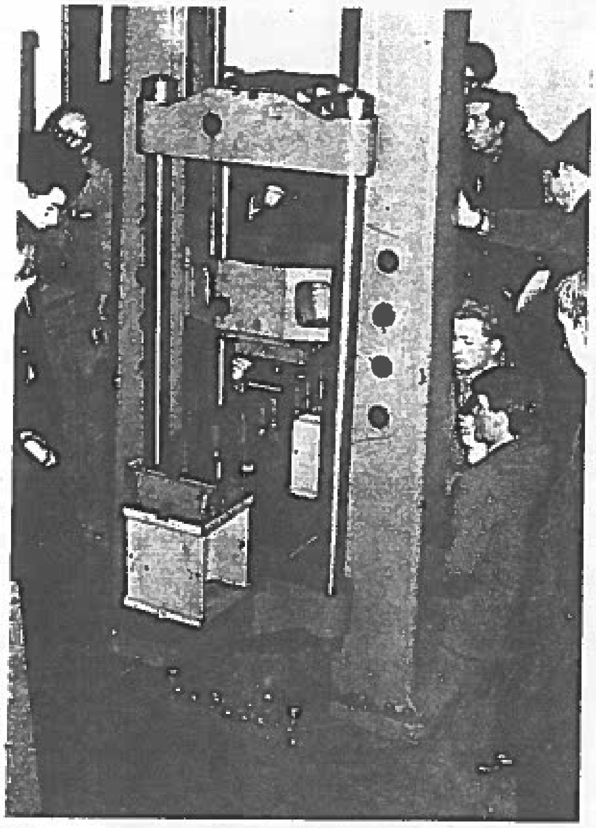
Four two-hour periods are allowed for this, all run on the lines of a seminar rather than a lecture; the participants are encouraged to ask questions at all stages, and to discuss points arising among themselves as well as with the demonstrator.

In the first period, most of the time is devoted to describing the problem, running through the printed notes and getting the philosophy of the course across. To break up the talking a little and, more importantly, to make sure the boundary conditions of the problem are understood, the class are taken to the laboratory and shown the test rig. Some time is left at the end of the period for a start to be made on considering a shape; and here the demonstrator encourages the adoption of differing solutions by all the groups.

The second period starts with a brief talk on the design of connections, with emphasis on the likelihood of premature failure in connections rather than design failure in members. Most of the period is devoted to detailed design, with the demonstrator discussing points with each group in turn and lecturing briefly to the whole class on points found to be generally misunderstood. By the end of this period, the whole class should have completed the main outlines of their designs and be more or less ready to draw.

Drawing occupies most of the third and fourth periods: but at the beginning of the third a short talk on drawing is necessary, both because drawing on tracing paper has not been attempted before and a few points of technique require emphasis, and to try to ensure that the final drawings contain all the necessary information for construction. Despite these general comments and the individual assistance given to each pair by the demonstrator,

Fig. 4—TESTING: A second year class in the laboratory during a test. A sheet-metal spot-welded beam (problem No. 1) is under test in a 100-ton Avery Machine.



drawings still get produced lacking sufficient detail, and the missing parts have to be guessed during fabrication.

There is a dead-line for handing in the drawings, and the class is pressed to keep to this. At this point, two prints are taken off each tracing and one is retained, the second being passed to the workshops for the fabrication stage.

(2) FABRICATION

Before starting manufacture, the class are encouraged to make a start on their reports, while the calculations are still fresh in their minds, and they are given some idea of what these reports are expected to contain. Only a small proportion take this advice.

For the next five periods the class are fabricating their structures, each group building to its own design. During this period, they are under the supervision of two craftsmen in the workshops, from whom, it is hoped, they may acquire some useful tips about the more practical behaviour of the material they use. Fig. 3 shows a group in action. At this stage, while alterations to the design are permitted—most designs need some to enable them to be constructed—any such changes are noted on the drawings.

Once more, there is a dead-line for completion, and the pressure in the workshops rises noticeably as this date approaches.

(3) COSTING

Before testing, the structures are costed by the joint effort of a laboratory assistant and the demonstrator. This is done on a system which allows for an approximately correct balance between labour and materials for the type of structure being considered. The structures are weighed, so many units of cost per pound of material being allowed, and for the riveted trusses the fasteners are counted. Labour is costed on a system which, as far as possible within the general scheme, penalises special or awkward construction and places a premium on simple square cuts. It is thus possible for the designers, although they are not told too much about the details of the costing system, to make a general decision between a simple heavy structure and a light complex one. To aid the costing process, printed sheets have been prepared, and the designers are handed these to include in their reports. The structures are at the same time checked against the second copy of the drawing for alterations.

(4) TEST

On the day of the test, the demonstrator is able to see how well he has conveyed the idea that design is a worthwhile exercise: and so far our experience has been that there is considerable enthusiasm and interest not only in the performance of their own structures but in those of the rest of the group. Fig. 4 shows a group testing.

The structures are arranged in descending order of cost, and the most expensive tested first; this keeps the tension high until the last structure, for the class "winner" is the cheapest to comply with the conditions. Each group tests its own structure, first giving a very brief dissertation on its merits and the reasons for their choice of design. The demonstrator comments on the good and bad points of the design and on the workmanship, and attempts to explain the resultant failure, hoping that it bears some relation to his previous remarks.

(5) REPORTS

The groups then go away to complete (or write fully) their reports, which must be handed in for marking a few days later—again to a dead-line. The report is assumed to be angled for a busy managing director, who has commissioned this prototype structure: emphasis is placed on concise-

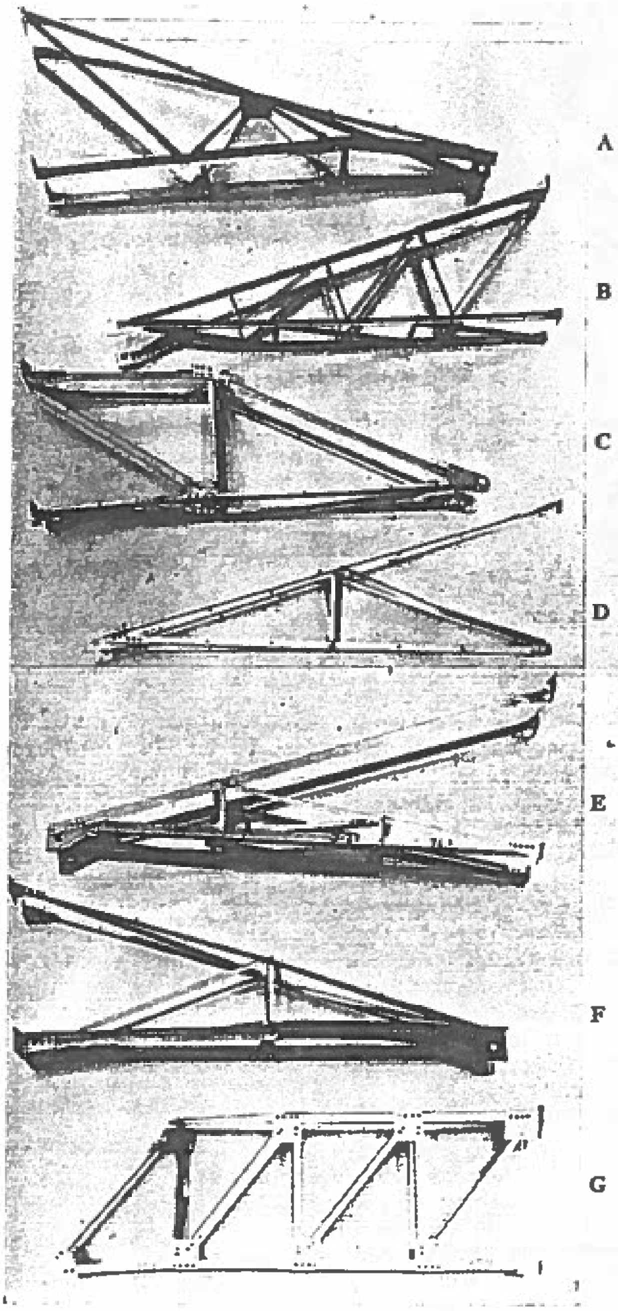


Fig. 5 (Above)—FIRST YEAR DESIGNS: Problem No. 1 Cantilever truss, 32 in. over-hang, minimum collapse load 600 lb. Steel angle and pop-rivets.

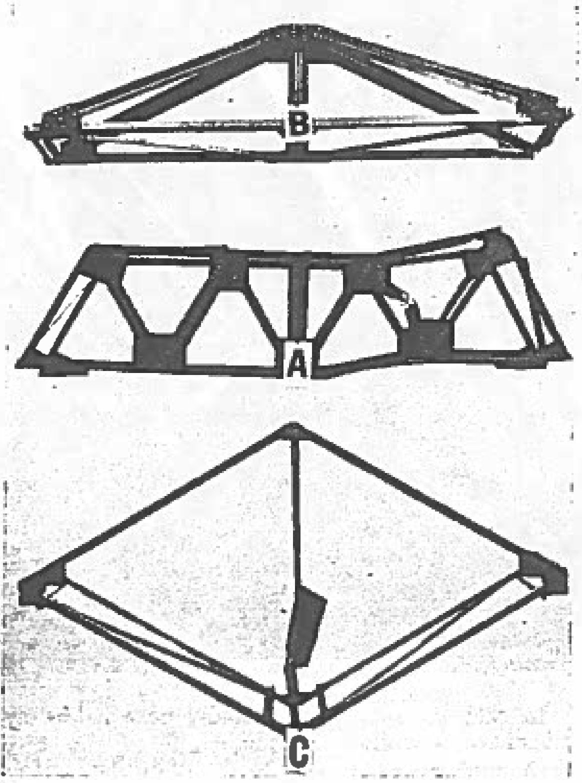


Fig. 6 (Right)—FIRST YEAR DESIGNS: Problem No. 2. 33 in. span girder, minimum collapse load 1 ton. Steel angle and pop-rivets.

ness, on justification of the structure chosen rather than explanation of design processes, on facts rather than opinions. The problem is stated, the chosen solution shown and proved to be adequate, the test described and, most important, a brief description of the modifications thought desirable to improve the strength and/or reduce the cost in the light of the test results.

Great care is taken at this stage to make sure that the maximum benefit is derived from the course by going through each man's report individually with the structure and drawing before him; and here two demonstrators are necessary so that the two members of a group may be seen together.

Typical Designs

(1) GENERAL REMARKS

Some 200 structures have been built to date, of a wide and entertaining variety. It is only possible to illustrate a very small selection of these here and to discuss the designs in general terms. With designers as inexperienced as first and second year undergraduates one would not expect a high standard. In fact, the results obtained have been most encouraging. The quality has varied widely, but there has been a remarkably good number of sensible, well executed designs.

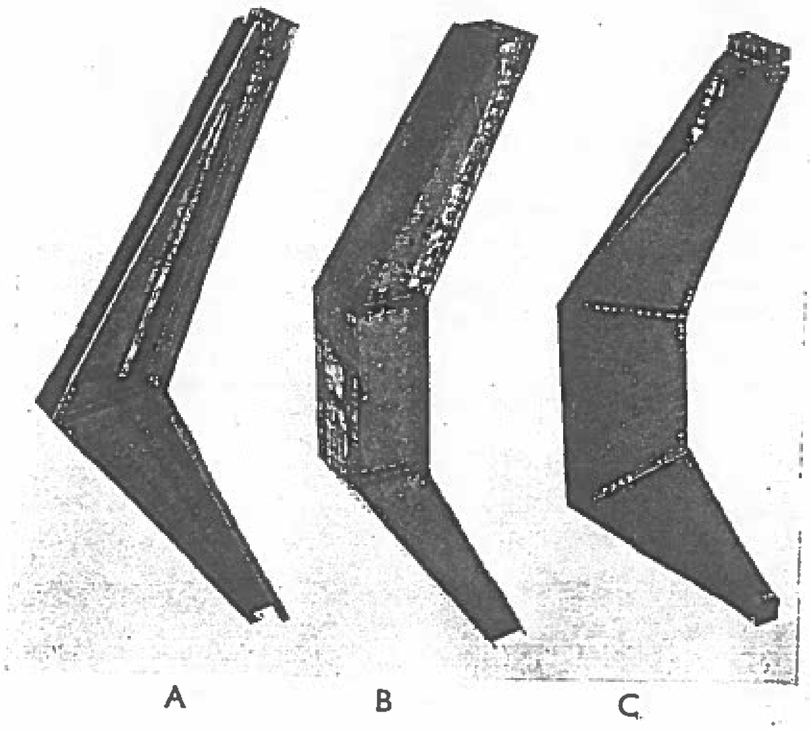


Fig. 10—SECOND YEAR DESIGNS: Problem No. 2, cranked column, 36 in. long, 2 ton minimum collapse load, Steel sheet, spot-welded.

The cranked column Problem No. 2 is again more difficult. Fig. 10 shows three solutions taken from one class. The single-web structure A, weighing 9.85lb., was weak in torsion and buckled laterally at a low load. Structure B was a straightforward parallel sided box design which reached the required load (2 tons) for a weight of 11.56lb. Structure C is an ingenious and more imaginative solution, which was also successful and weighed 9.50lb.

Assessment

(1) PLACE IN THE COURSE

The design projects described in this paper are, so far as we are concerned, essentially a new type of laboratory experiment. They are lengthier and more demanding than the more formal kind of experiment, but this is nevertheless their true place in the course. Their great value is in stimulating the interest of men who are just starting their engineering education. They are not intended to illustrate current technological practice, and must not be confused with the more specialised and advanced kind of design work given to students in civil and mechanical engineering departments elsewhere or our final year Fast Course Men.

They fit in especially well with the general type of degree course operated at Cambridge. But they could also have something to offer as first or second year projects at more specialised engineering schools.

(2) STUDENT RESPONSE

The most striking impression we have gained after running these courses for three years is the enthusiasm they generate in the undergraduates. To a certain extent this might have been expected during the previous years, when the participants were volunteers. But this year, with design now compulsory for Normal Course freshmen, the high level of interest has continued unabated.

(3) SIMULATION OF DESIGN INVOLVEMENT

We would not suggest that our simple exercises have much resemblance to real-life design, which is a highly complex affair. The number of variables is strictly limited, and the material and mode of fabrication prescribed. Nevertheless, the men are for the first time put in the position of having to create something from scratch, however simple, and make decisions. This, we think, is highly important.

The course would be far less effective if the students had only to work out their designs on paper and not build them. The need to see his design through, in every detail, instils a feeling of responsibility in each man, which makes him take the course much more seriously than would otherwise be the case, and enjoy it.

(4) OBSERVATION OF FAILURES

Not least of the benefits to be derived from such courses is the chance to observe actual failures taking place. Each man, apart from anxiously watching his own structure under test, is able to see the other six or so structures of his class being tested to destruction, and observe the variety of failures which take place.

(5) TIE-UP WITH LECTURES

The first year problems depend very little on the current lectures, and are indeed given to some men in their first week. They are thus little help in putting over the immediate lectures. They do, however, give an insight into buckling problems, which helps the understanding of some later lectures.

The second year exercises come at just the right time to back up the theoretical treatment of bending of beams given in lectures. They thus show that some things in lectures are useful, but at the same time reveal the limitations of a purely theoretical approach.

(6) WORKSHOP PRACTICE

As a by-product the men derive some benefit from actually setting out and building their structures themselves, and from being in contact with craftsmen in the workshops.

(7) TIME INVOLVED

Unquestionably, the main criticism levelled at our design projects is that they tend to take up too much of the men's time. Each exercise, including design, fabrication and test, consumes a man's normal hours of laboratory work for four weeks. At this, it is definitely worthwhile, but it is a bad thing when a group design themselves a complicated structure and have to put in a lot of spare time work to get it built in time. To try to prevent this we put great stress on the desirability of a simple design. The introduction this year of a costing system, with a considerable allowance for labour content, is helping to keep structures simple.

(8) STAFFING

The practice of making each class the responsibility of one member of staff from start to finish has worked well. One man can comfortably control a class of 12 to 18 men, the contact time being 8 to 12 hours. Much depends on the class leader and his ability to make the men feel it is up to them. At present, while the course is still fairly new, teaching staff have enjoyed this type of work. Care has been taken to organise things so that nobody instructs on the same problem twice running. The thing that must be avoided is for such a course to become stereotyped, with the same lecturer giving it year after year.

(9) NEED FOR OTHER PROJECTS

The other criticism is that all the present problems are structural. This has come about, not due to any desire to specialise in this field, but simply because these are the easiest kinds of problems to devise. Mechanical exercises on the same design-build-test principle, which are simple enough and cheap enough, are hard to devise. Nevertheless, we plan to try some mechanical problems in 1966–67, and the following have been suggested as feasible:

Centrifugal pump,
Front suspension for bicycle,
Refrigerator.

We would also like to see electrical projects introduced.

Conclusion

Design-build-test exercises of the type described, simulating design involvement, have proved successful. They are now a regular part of our laboratory work, involving truss-type structures in the first year and sheet-metal fabrications for the second year. Each lasts four weeks.

It is important to make sure that the men have no preconceived ideas when they start designing. Previously built structures to the same design must be hidden away.

The introduction of a costing system which includes an allowance for labour content, instead of merely assessing the designs by weight, has made the course more realistic and helped to keep the structures simple.

Equivalent exercises of a mechanical and electrical nature are badly needed.

Acknowledgements

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