FOLD-UP CONCRETE CONSTRUCTION

by

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SUMMARY

The fold-up method of concrete construction is a relatively new method of precasting a variety of structural shapes on a single flat surface and then folding portions up to form a three-dimensional shape. Structural members as beams, girders, columns, piers, footing, and retaining walls — all having applications in bridge or building construction — may thus be formed. Flat-cast panels, properly articulated, can also be folded up to form a variety of surface structures for architectural use.

The advantages of fold-up construction over other types of precasting are those of simplicity, ease, and economy. The advantage of economy is particularly decisive for one-of-a-kind or individualized precasting as the need for expensive once used forms is eliminated. In some cases, fold-up construction greatly reduces the hauling weight of large precast components as well.

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INTRODUCTION

There is tilt-up, lift-slab, slip-formed, and segmental construction. Now there is fold-up concrete construction. Just what is fold-up construction all about? In essence, it is nothing more than the familiar operation of paper folding (Origami, as it is called by the Japanese), done with flat-cast concrete panels instead of paper. Folding is done along preformed joints in the cast concrete through the mechanism of bending the reinforcing steel extending across the joint or, in some cases, simple hinges welded to the reinforcing steel.

Precasting structural members by conventional methods is an excellent way to produce concrete units, provided enough of

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the same units are produced to justify the expense of fabricating the original form. However, in many structures, as in bridges, concrete components are often one-of-a-kind shapes; precluding the economical use of normal precasting methods. Fold-up construction meets this problem by permitting easy and economical casting of the desired shape.

Examples of various applications of fold-up construction are presented in the sections following. Discussed are examples of beams and girders, columns and piers, footings and retaining walls, and surface structures.

BEAMS AND GIRDERS

Compositely acting, thin, stay-in-place, precast concrete forms have proven to be both effective and economical when used in the construction of concrete bridge decks (1,2). These thin, flat forms serve not only as the support but also act structurally with the deck slab concrete upon hardening of the in situ concrete.

An extension of this method for beams and girders would be to cast a thin exterior shell of reinforced or prestressed concrete and then fill it with reinforcing steel and concrete. Posttensioning of the completed flexural member could be carried out if desired. Provided the precasting of the exterior shell is done economically, the advantage of this method is that it would greatly reduce the hauling and handling weights of such members, which at times are excessive for large members. At the same time, no field forming would be required as concrete would be placed directly into forms or molds. These molds would be designed to act compositely with the field placed concrete, as is the case in stay-in-place deck forms of concrete.

To meet the need for economical casting of the shell, a fold-up method could be used. This procedure is employed to best advantage when only a limited number of the particular shape shell members are required. (For large numbers of shells, conventional methods of casting are best.)

Although no full-scale beams have been cast using fold-up forms, a pilot study of small-scale beams has been carried out (3). The main features of this study are here described.

A conventional solid reinforced concrete beam 10.2 cm (4 inches) wide, 12.7 cm (5 inches) deep and 96.5 cm (38 inches) long was cast with two #3 billet steel reinforcing bars positioned 2.5 cm (1 inch) (clear distance) from the bottom. A second beam with the same dimensions and reinforcing was cast using the fold-up method. Figure 1* shows the first step in the flat-casting of this test beam. The panel shown is 2.5 cm (1 inch) thick and has a 16 gage welded steel wire fabric with a 5.1 cm (2 inch) grid each way embedded in the panel. The steel wires extend across the 2.5 cm (1 inch) wide fold lines, which are created by strips of cellular plastic. Edges which are to fold together

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*All figures are attached.

also have the reinforcing steel projecting from them for joining purposes. Note that the surface of the concrete is grooved. This grooved surface will be the inner surface of the shell when folded and is intended to assist in developing composite behavior between the precast exterior shell and the in situ concrete placed later. The average strength of all concrete used had an ultimate strength of 29.8 MP_a (4,326 psi).

Figure 2 shows the panel after stripping the forms shown in Figure 1. The use of cellular plastic at the fold lines makes stripping at these locations rather easy. However, flat or beveled strips of wood also could have been used.

Figure 3 shows the panels folded into the beam position to form a voided shell. As the reinforcing wire was small in this model, folding presented no problem. In larger beams or girders for which larger reinforcing will have to be used, bending of the concrete surfaces may require some special apparatus as hydraulic jacks.

An alternate method to bending the reinforcing steel at the fold lines is to weld a few simple hinges to the reinforcing steel at the fold lines. The effort to fold the panels then becomes minimal.

Joining of the folded up edges is another aspect unique to this method. In this test beam, the protruding wires were merely twisted together. However, if large size reinforcing steel is used in a full size member, the extended steel could be joined by laying in a reinforcing bar along the joint and welding it to the extended steel.

The amount of steel required in the shell would depend on handling forces on the shell itself, and on forces imposed by the addition of the infill concrete. Because of composite action, most of the steel in the shell would continue to be beneficial for sustaining the superimposed live load as well as the dead load on the member.

After folding, additional reinforcing steel as needed would be positioned inside the shell and secured. See Figure 4. High bond mortar or concrete is needed to fill in the corners at the fold lines. Unless the shell is exceptionally thick, hand trowelling could be used to accomplish this task.

At this point, the completed shell would be shipped to the construction site for erection. Hauling and erection weight is greatly reduced as a large part of the beam mass is absent at this stage. Once the member is in position, the last step is to fill in the shell with cast-in-place concrete, as in Figure 5.

To examine the structural behavior of this fold-up test beam, after 28 days of curing it was put in a Universal testing machine and loaded at the center of the span. The end bearings, 0.86 m (34 inches) apart, were simple supports. Electrical resistance strain gages were placed at the top of the beam, one on the shell and one on the infilled concrete. A dial gage to measure maximum deflection was also positioned under the beam. The same test setup was used for the conventional reinforced concrete beam.

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The results of the tests are shown in Figures 6, 7 and 8. In comparing the data, the following conclusions can be drawn:

1. For corresponding loads, the strains (or stresses) and deflections in the fold-up beam are somewhat less than those for the conventional beam. This difference is attributed to the extra reinforcing steel contained within the shell itself and does show that such shell steel is effective in resisting superimposed loads.
2. There is some slippage (about 8%) between the infill concrete and the shell concrete in the fold-up beam. Petrographic examination of the interface between the shell and core concrete did reveal a thin layer of carbonation on the surface of the shell. Such carbonation is normal on the surface of all cured concrete.
3. The ultimate load for the fold-up beam is appreciably larger than that for the conventional beam. This result, however, is not particularly significant as failure of the conventional beam was caused by diagonal tension as no web steel was used. The wire fabric contained in the shell of the fold-up beam provided the web reinforcement for this member.

By all present laboratory indications, fold-up beam construction appears to hold promise. Actual full-scale construction may uncover some aspects not foreseen in the small-scale laboratory tests. However, the principle seems to be worth pursuing.

Although a simple rectangular beam section was used in the pilot test, it is quite conceivable that other beam shapes as channels, box beams, and I beams could be generated by the same fold-up technique. The channel and box shapes can in fact be produced by simple folding without the need for any infilling at all.

Furthermore, such beams might be adapted to prestressing through the inclusion of posttensioning strands in the shell in lieu of standard reinforcing bars. Here again, full-scale tests should be made to investigate composite action in a prestressed system. Theoretically, there is no reason why the flat-cast shell itself could not be prestressed through pretensioning as is now done in deck forms (1,2); however, practical considerations would probably adversely affect the cost.

COLUMNS AND PIERS

Other bridge elements as columns and piers could also be produced by the fold-up method. Figure 9 shows one of many possibilities for the flat-casting of a large compression member. Small members could indeed be precast as is now done and easily transported to the construction site. However, large members cannot be precast because of weight restraints. As such, they are cast-in-place in the field using a variety of form work systems. The construction of this form work is often expensive, particularly if the form is used but once.

The fold-up form not only minimizes the cost of form making, but also acts compositely with the inner core, consisting of reinforcing steel and concrete. The cross sectional shape can be of any polygonal configuration as square, rectangle, triangle or hexagon.

In practice, the fold-up shell would be precast either on or off site and placed in position. Into the hollow core would be placed a reinforcing cage of steel. Allowing for the steel in the shell itself, the amount of core steel could possibly be reduced. Infilling of field placed concrete would then complete the construction.

No actual structural tests have been made to date on such a column or pier. There is no question that the fold-up form could function adequately non-compositely; however, a series of laboratory tests should be undertaken to establish the degree of composite behavior developed in compression.

FOOTINGS AND RETAINING WALLS

Almost without exception, the casting of concrete foundations as footings, pier caps, retaining walls, abutments, and the like is a one-of-a-kind situation because of soil and site differences. As such, foundations have heretofore virtually defied economical attempts at precasting of these concrete units. Fold-up forming may provide the economical answer.

Figure 10 illustrates how prefabricated edge forming for footings or pier caps could be easily done. The forms might be shipped flat or prefolded. No on site carpentry work would be required.

After the folded forms are set in place, reinforcing steel and infilled concrete are placed as previously described for beams or columns.

A somewhat more challenging problem is that of prefabricated retaining walls. Various modular precast concrete systems have been tried with varying degrees of success. Where many repetitive units need to be cast, conventional casting methods work well; however, where single precast units must be made, they are uneconomical.

Figure 11 shows a possible solution to the latter problem for a retaining/abutment wall situation as commonly occurs in bridges. In concept, the piers with their foundations would be designed to take the full overturning moment of the lateral soil pressure. In addition the piers would of course take the vertical forces of the bridges. (As these piers would be relatively large, they could be constructed with fold-up shells as described in the previous section.) The retaining wall planks would be flat-cast as shown in Figure 11. These concrete planks are then attached to the pier the full height desired. Note that no foundation or footing of any kind would be required under this wall. It is assumed that all bending and shear forces in the wall planks would be transmitted only to the piers.

The out-of-plane wing walls could be formed by merely bending the planks along the preformed fold line and then grouted. Any angle of bend could be made from the originally flat planks.

Here again, no tests have been carried out for such a retaining wall, but the concept looks promising by virtue of its

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simplicity and versatility. Because of the diverse kinds of problems one encounters in foundation design, a degree of creativity is to be encouraged to seek the many possible ways that a flexible system as fold-up forming might be employed. The examples shown are but two of many dozens possible.

SURFACE STRUCTURES

A surface structure is defined as a structure whose forces are transmitted through surface elements (either flat or curved) rather than through linear elements. For example, a folded plate roof or a thin dome would be a surface structure, while a beam or truss would not be.

Many useful structural forms may be created by the contiguous arrangement of flat surfaces (as the many shapes of folded plate roofs testify). The ancient Japanese art of Origami paper folding further illustrates the infinity of configurations one may make from an originally flat surface. There is no theoretical reason why large surface structures cannot also be made in reinforced concrete using the fold-up techniques under discussion.

Work by the writer (4,5) provides a considerable amount of background for the concept of fold-up, or articulated, construction. As described in a recent concrete journal (6) commercial flat-casting of room size surface structures by Foldcrete International, Inc., is already a reality. The patented Foldcrete technique was developed in 1968 by D. W. Johnson and W. C. Harr, both of San Francisco. In concept, reinforced concrete floors and walls are flat-cast on the ground, with the floors and walls connected by simple hinges welded to the reinforcing bars. When the wall elements are folded up and joined, a complete room, including openings and miscellaneous projections, is thus formed. The folded joints are sealed with cast concrete.

These load bearing modular rooms are then erected for either low-rise or high-rise buildings as is done with conventionally made modular room units. Costs of this kind of fold-up construction have been about 10% less than for conventional concrete construction, with considerable savings in time.

As something of a "fun" project to explore further potentials of fold-up surface structures, the writer asked his class in structural design at the University of Virginia to make some small-scale surface structures of their own design and choosing. Figures 12-16 illustrate their results.

Projects shown in Figures 12-15 all use wire mesh as the reinforcing, carried across the fold lines to act as hinges. This concept is the same as used in the beam study (Figures 1-5). The structure in Figure 16 was reinforced with #3 steel bars instead of wire mesh. To make folding easier, hinges were welded to the rebars at the fold lines, somewhat as in the Foldcrete system. After folding,the joint was secured by welding the hinges solid and by grouting the joints.

Basic topological research on folded plate systems is being done at the University of Utah under the direction of Professor

Ron Resch. Using both models and computer graphics, he is exploring the innumerable possibilities for generating three-dimensional surfaces from folded flat forms. Figure 17 shows but one of the many complex and original forms he has developed in this manner. This figure shows the plan of a hexagonally bounded dome form of triangular planes, all generated from an originally flat sheet. To investigate the practical possibilities of producing such fold-up forms in reinforced concrete, Ron Resch has been in consultation with the Concrete Technology Corporation in Tacoma, Washington.

Although the immediate application of surface structures to bridges may not seem apparent, possible future bridge designs (tubular, segmental, prismatic, etc.) might well employ fold-up surface structures in some manner.

CONCLUSIONS

The description of fold-up concrete construction as presented in this paper is directed primarily at the discussion of concepts and ideas. Emphasis of application in this paper has been on bridge related structures.

Applications not mentioned could include such items as concrete drainage ditches, culverts, parapets, and crash barriers. The whole area of shelter or architectural application is but briefly mentioned.

In all areas additional testing and developmental work still need to be done. However, the concept of fold-up construction is so simple in nature that its advantages are intuitively obvious. It is the successful working out of the details of fabrication, particularly the folding, that will determine the eventual economy of the system. The potentialities of this new system appear to be worth the effort.

ACKNOWLEDGMENTS

The interest and cooperation of all the students who contributed to making the various models cited in this study are greatly appreciated. Greg Johnson, who made and tested the beams, is especially acknowledged.

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Figure 1. Flat casting fold-up beam.

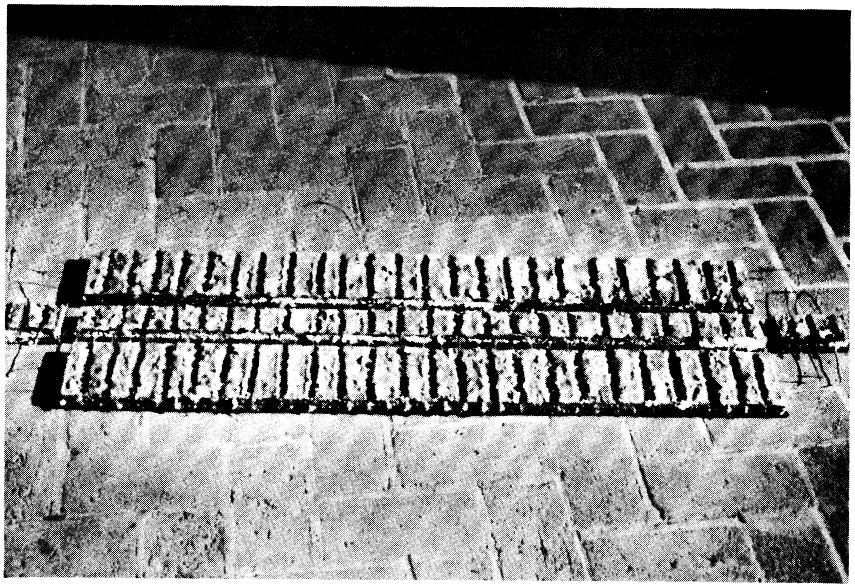

Figure 2. Stripped cast of fold-up beam.

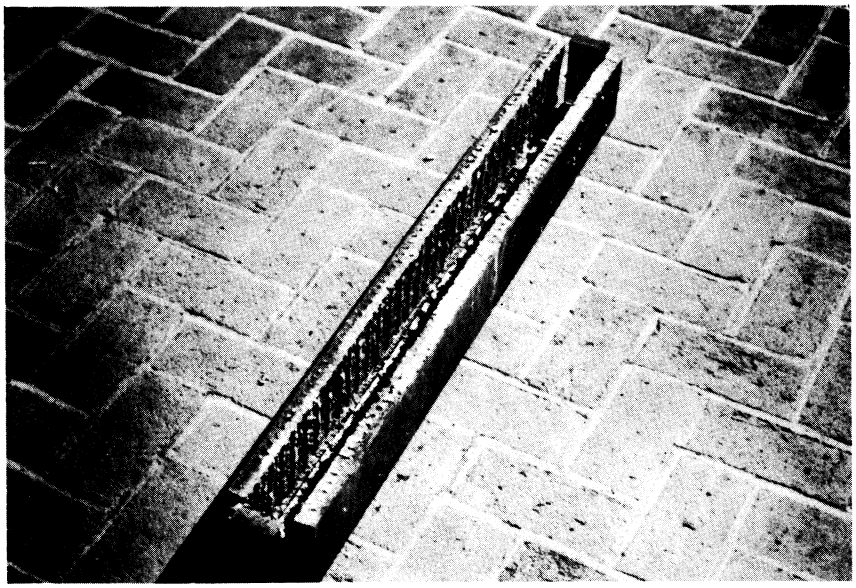

Figure 3. Folded shell.

Figure 4. Shell with reinforcing steel.

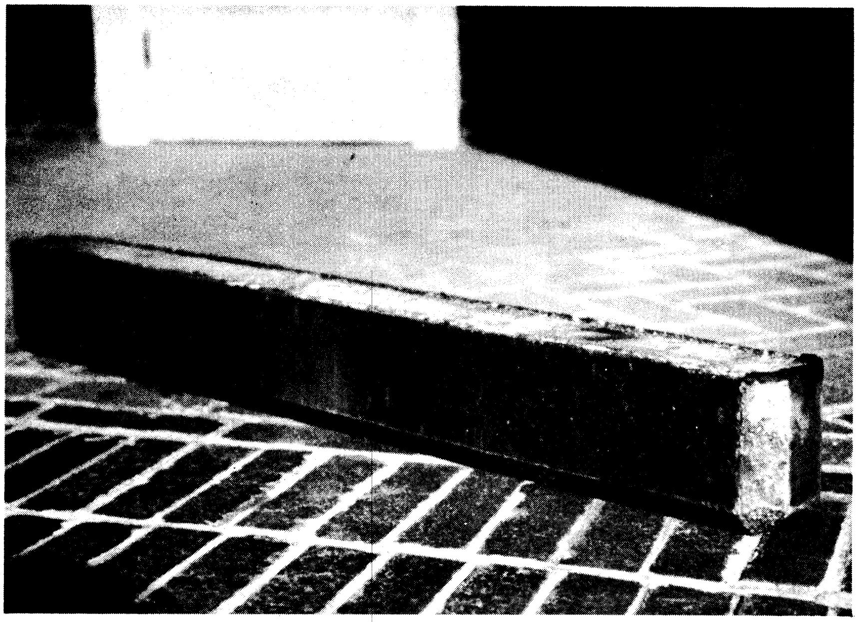

Figure 5. Completed beam with infilled concrete and grouted edges.

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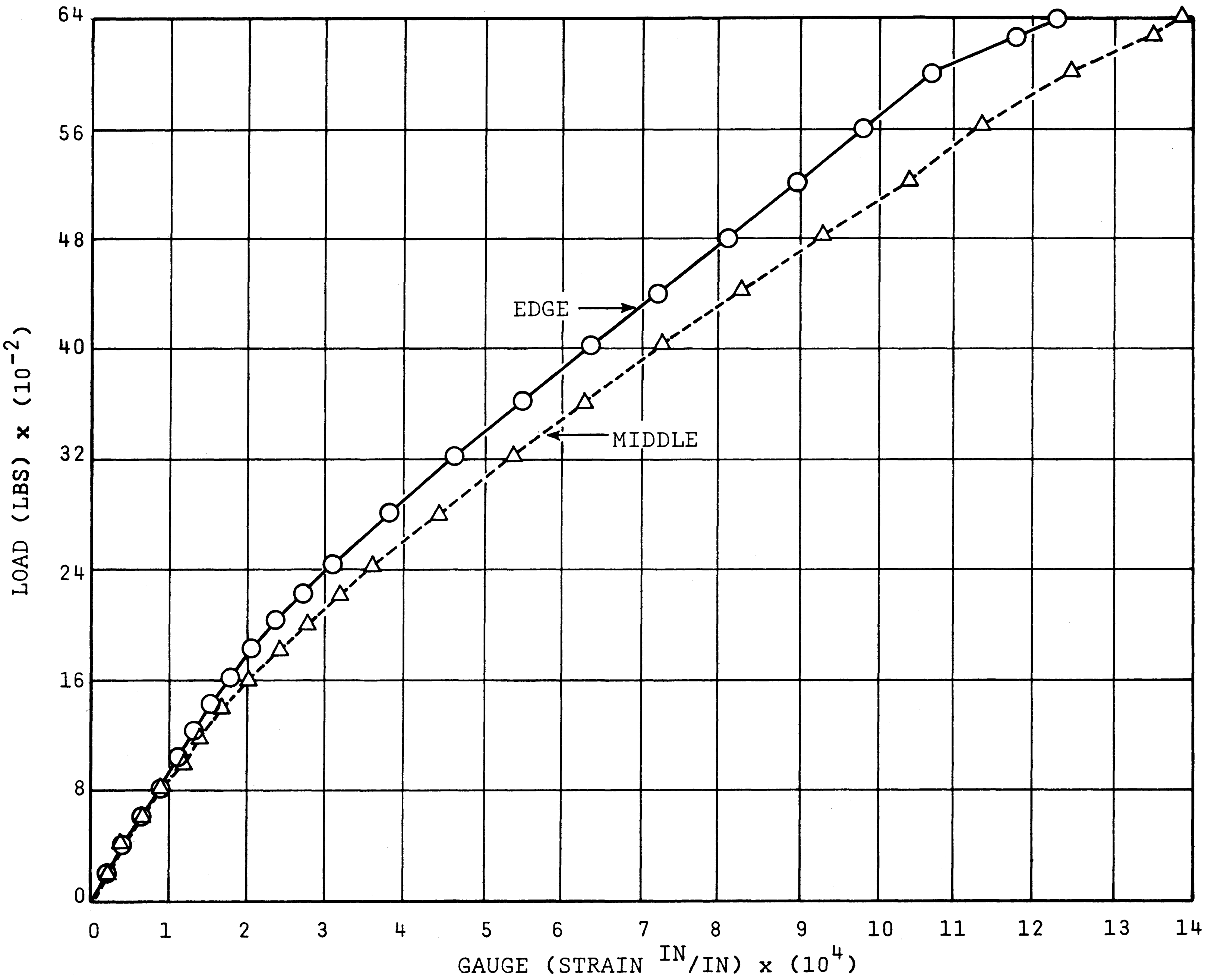

Figure 6. Load-strain diagrams for fold-up beam.

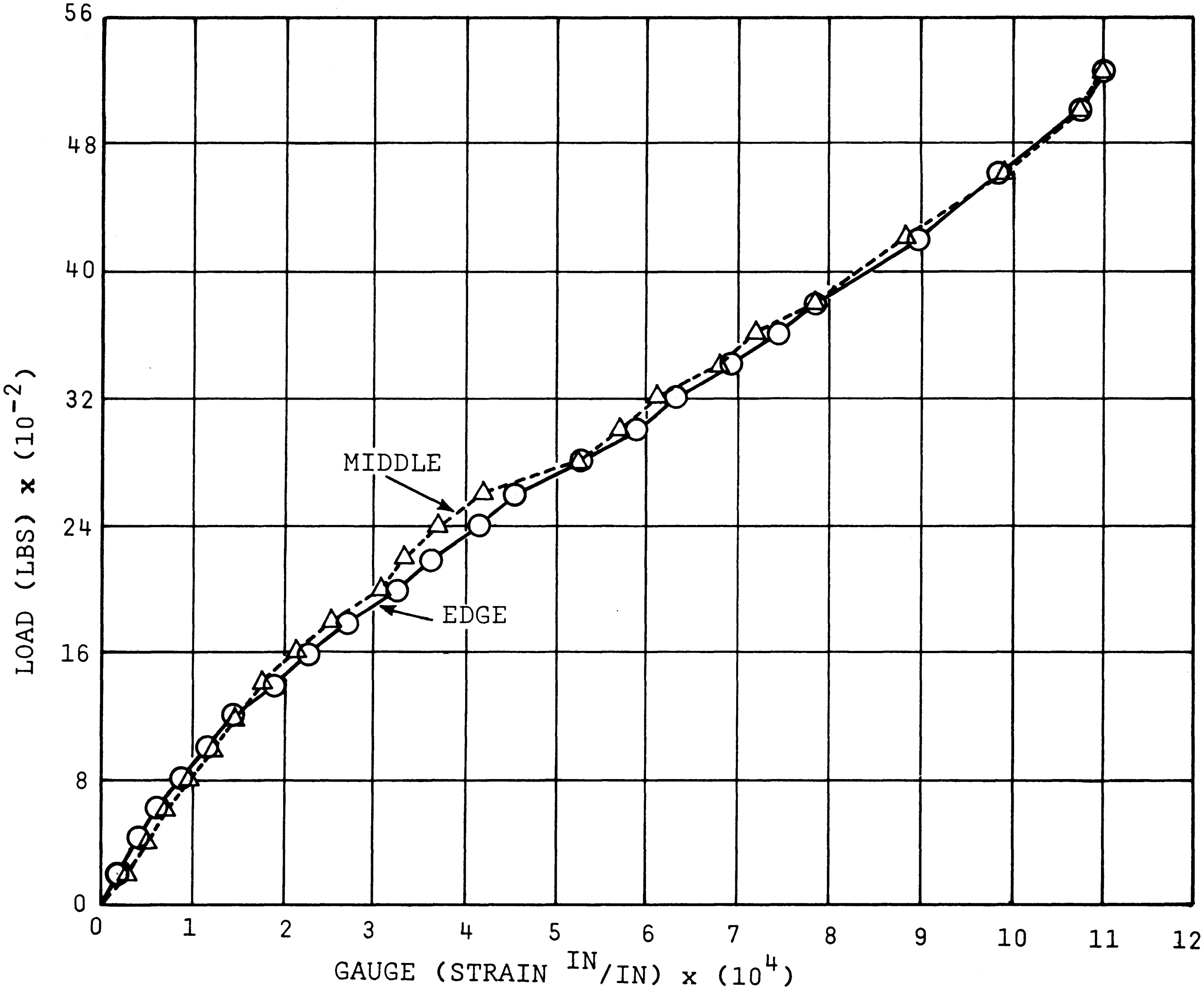

Figure 7. Load-strain diagrams for conventional beam.

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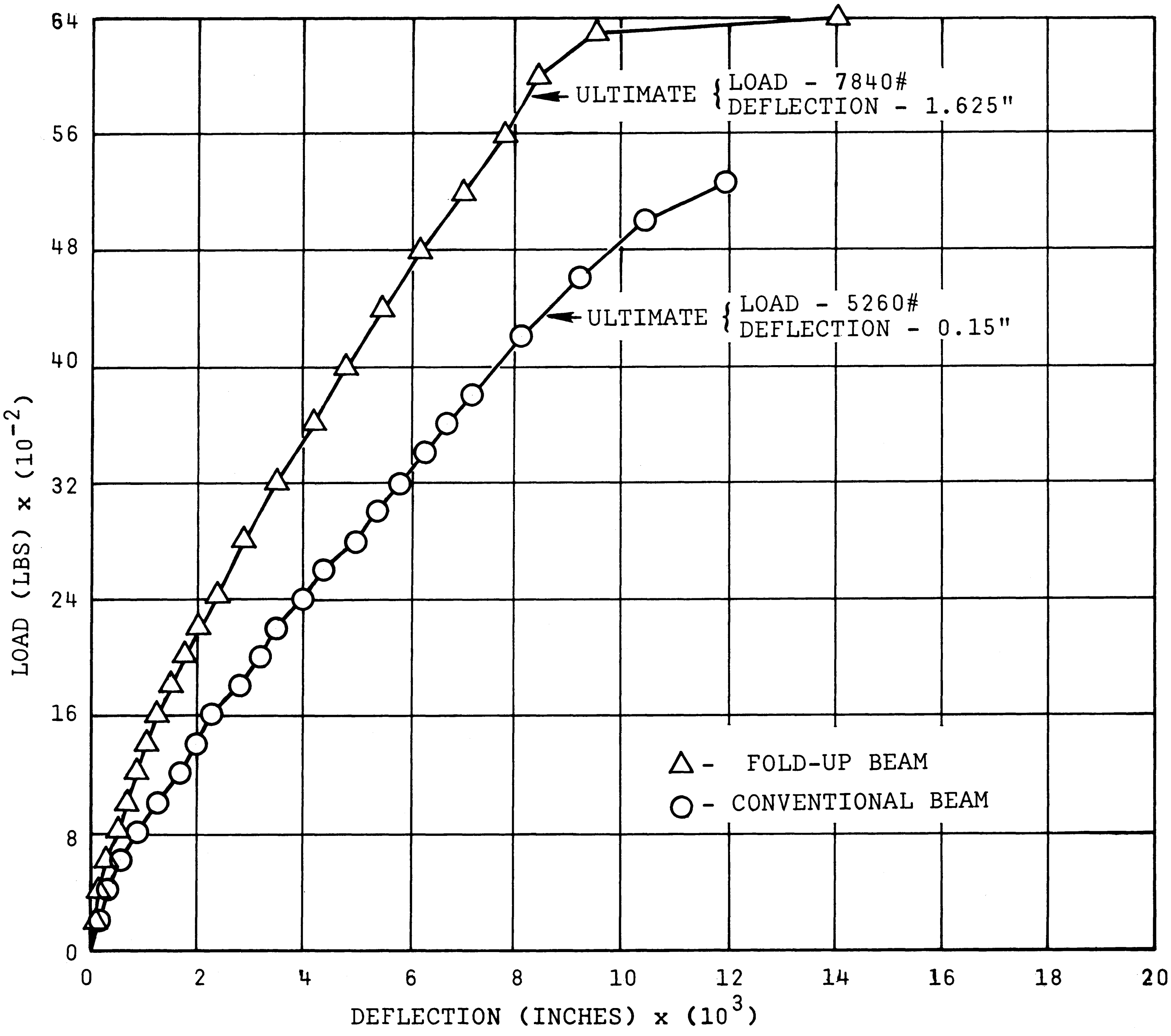
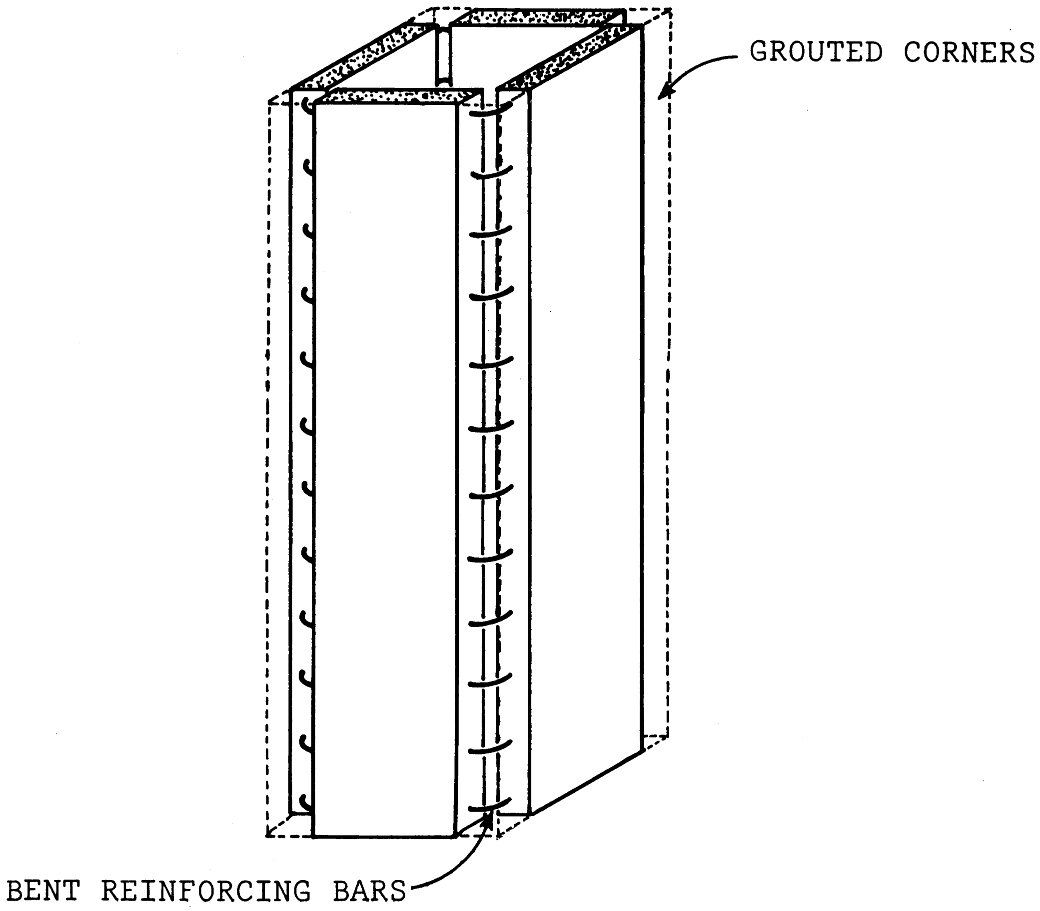
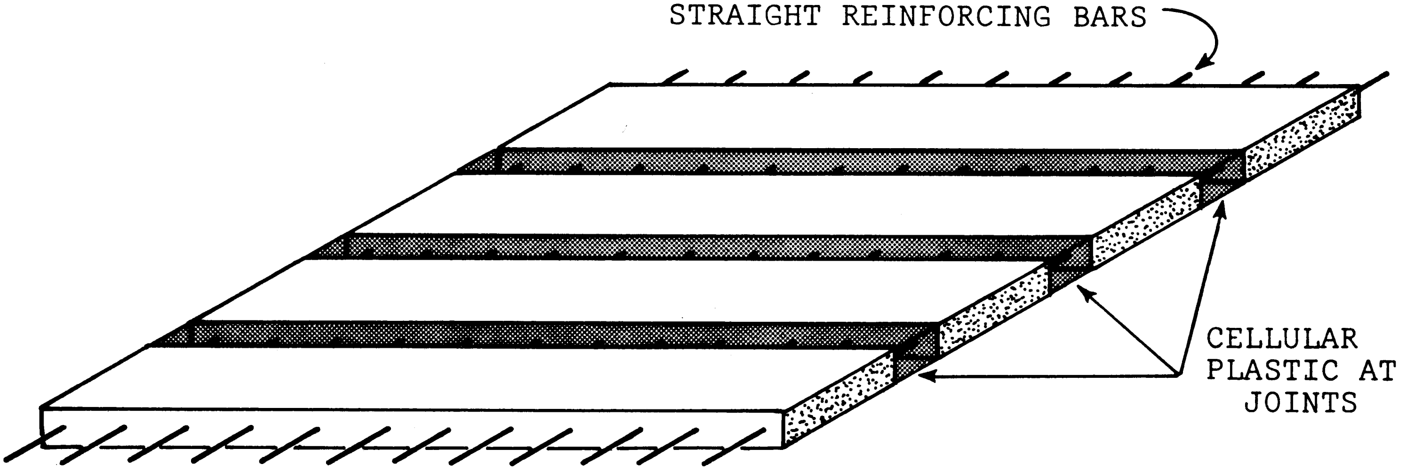


Figure 8. Load-deflection diagrams for fold-up and conventional beams.

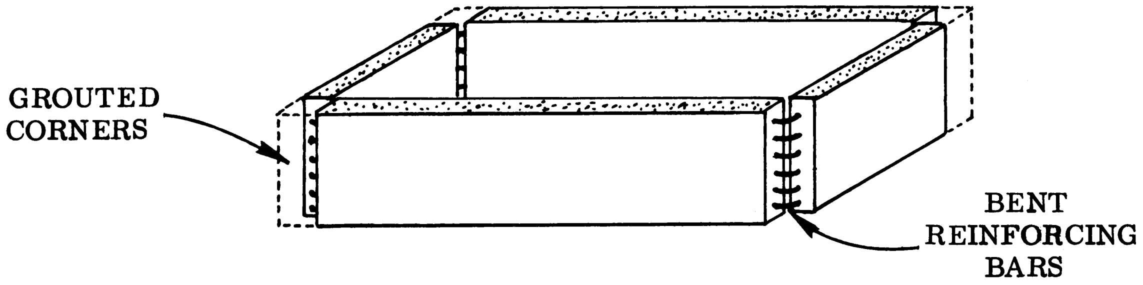


FOLDED PRECAST FORM

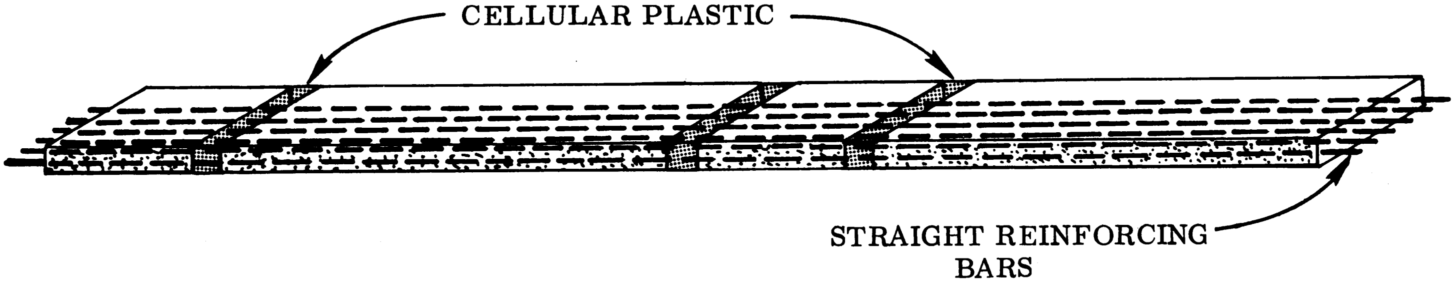


FLAT CAST SHAPE OF FORM

Figure 9. Flat-cast column shell.



FOLDED PRECAST FORM



FLAT CAST SHAPE OF FORM

Figure 10. Flat-cast footing form.

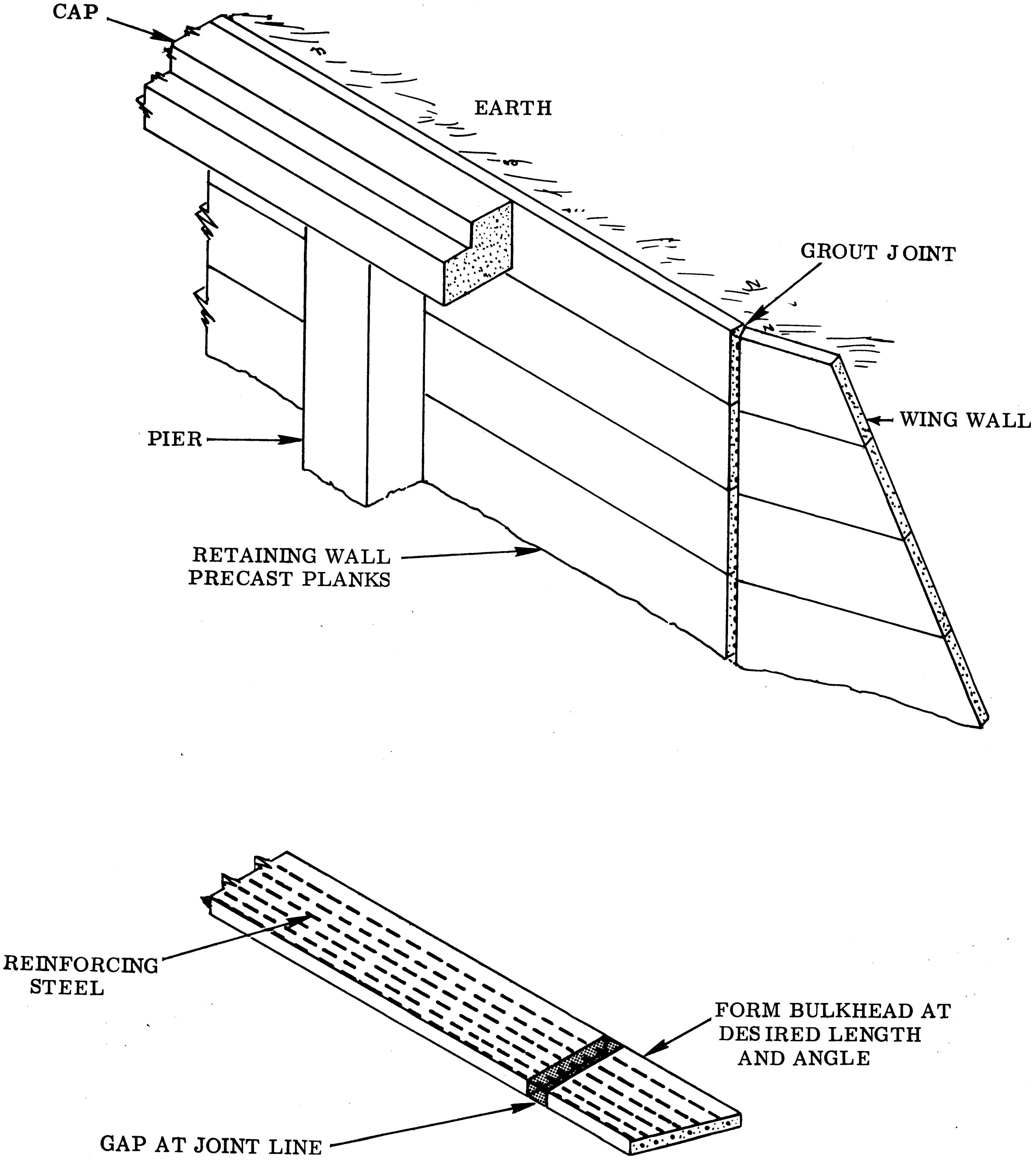


Figure 11. Flat-cast retaining wall planks.

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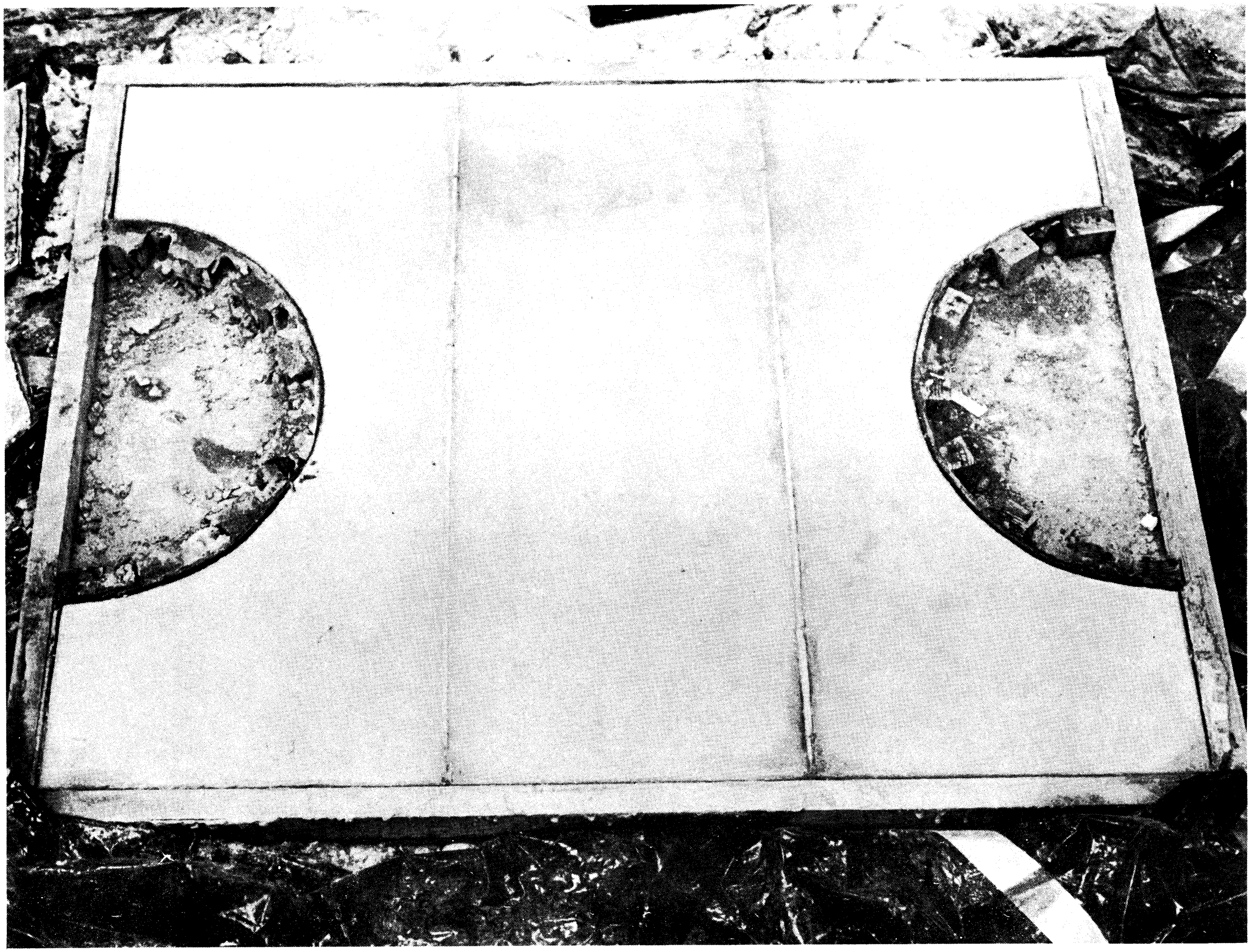

Figure 12. Flat-casting of a channel shape, a bench, by students S. Ours, K. Brown, D. Ruddy, B. Mullen and J. Blaine.

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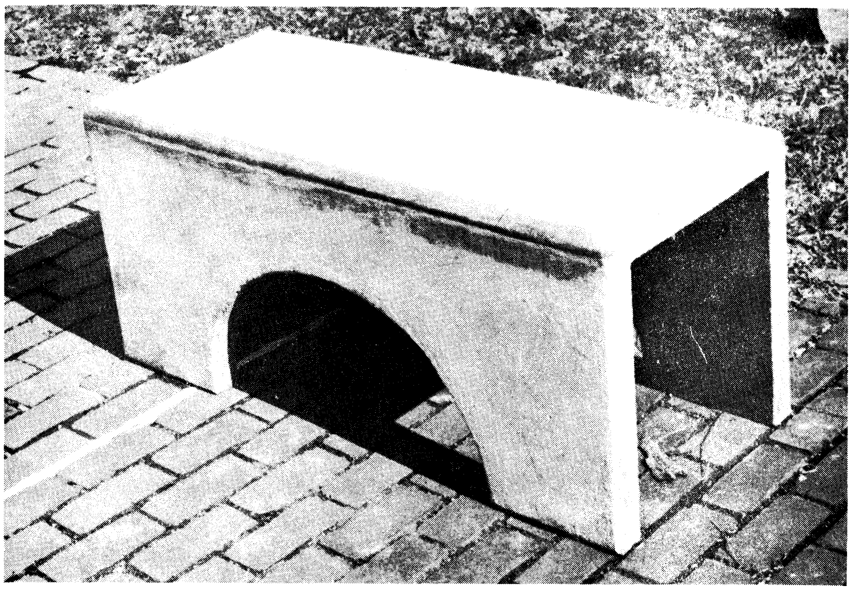

Figure 13. Completed structure, a bench, folded and grouted.

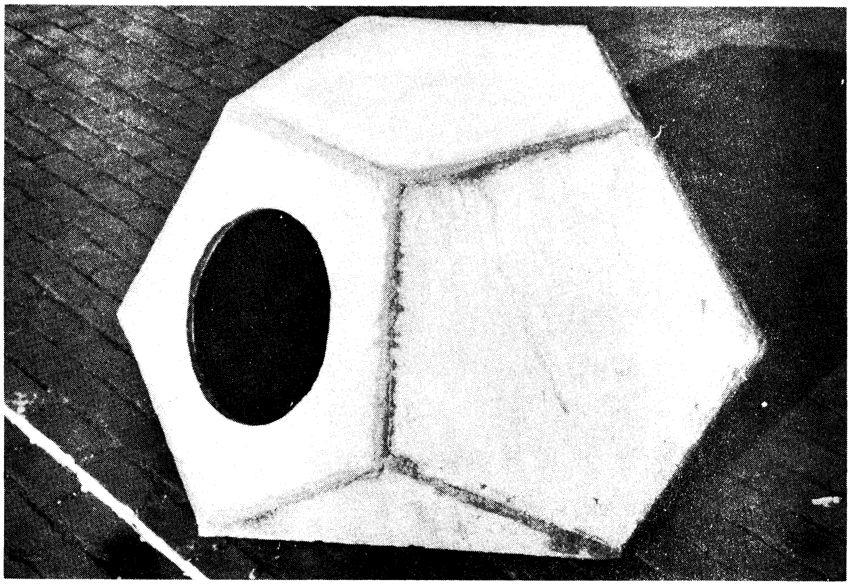

Figure 14. Flat-cast pentagonal surface structure, a dog house, by students C. Morris, T. Morris, W. Hellmuth, and E. Chambers.

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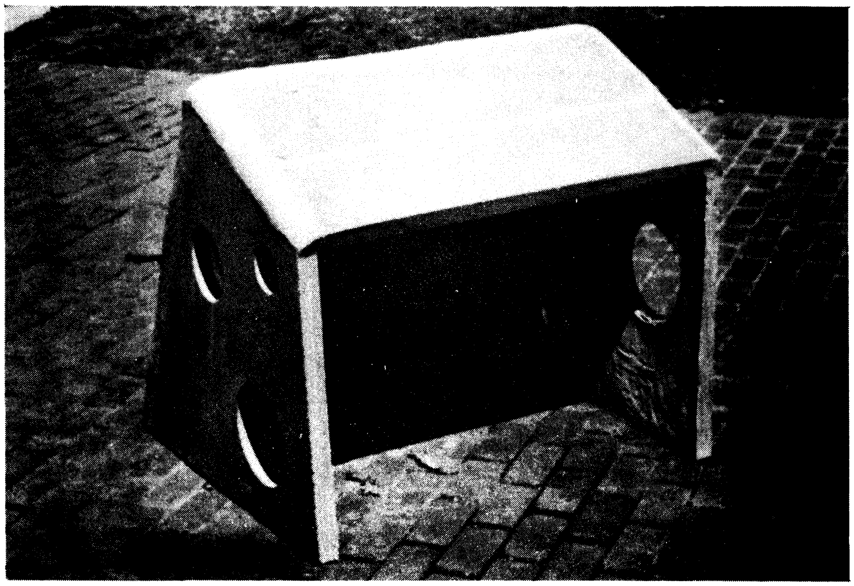

Figure 15. Flat-cast structure, a trash can screen, by students T. Armstrong, F. Schneider, S. Carter and N. Rankins.

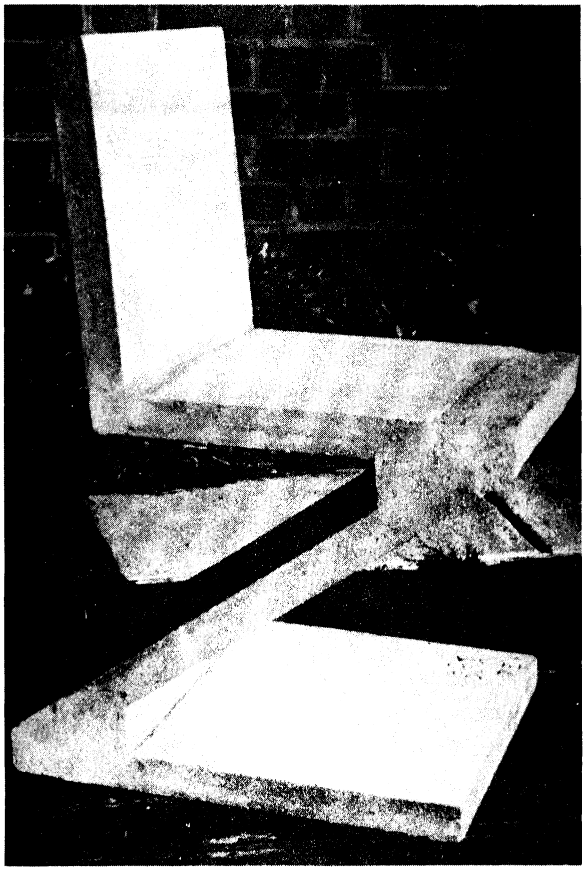

Figure 16. Flat-cast Z structure, a chair, by students D. Mruck and A. Kemler.

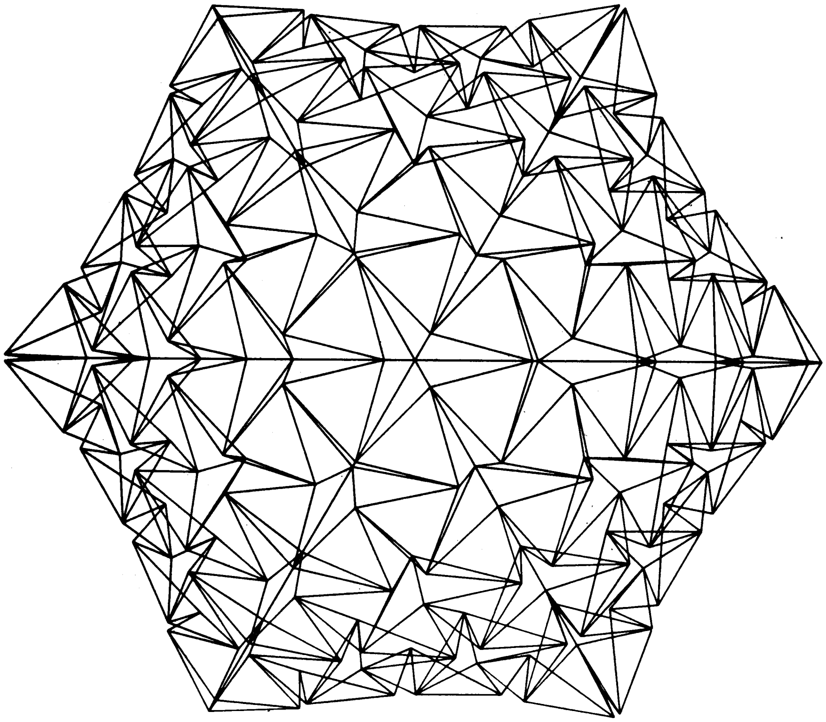

Figure 17. Folded dome as developed by Professor Ron Resch, University of Utah.

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