CIVIL ENGINEERING STUDIES

STRUCTURAL RESEARCH SERIES NO. 77

A SUGGESTED PROGRAM OF TESTS

for the

DEVELOPMENT OF CRITERIA FOR THE STRUCTURAL DESIGN OF REINFORCED CONCRETE BOX CULVERTS

By

C. P. SIESS

TECHNICAL REPORT
to
THE OHIO RIVER DIVISION LABORATORIES
CORPS OF ENGINEERS, U. S. ARMY
Contract DA-33-017-eng-222
Stage 5

JUNE, 1954

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

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I. INTRODUCTION

1. Introduction

This report covers Stage 5 of this project, relating to the additional tests needed to provide a basis for selecting design criteria for box culverts. Reasons are given why additional tests are needed, the types of tests required are listed and discussed in general terms, and an outline of the proposed tests is presented.

The discussions in this report are based on the studies made in Stages 1 through 4 of this project, and it is assumed that the reader is familiar with the previous technical reports covering those stages (1) (2).*

2. Scope of Stage 5

Stage 5 is defined in the contract as follows:

"Stage 5 -- The work for this stage shall be a re-examination of the test data, analyses, and correlation of Stage 4 with the object of ascertaining whether additional tests on reinforced concrete members or frames are needed in order to verify the theories developed and the extent of such additional tests; also, to extend the applicability of the information obtained over a sufficiently wide range to make them suitable for use in design. In outlining a program of additional tests, it shall be given in sufficient detail to permit its planning and execution by the Ohio River Division Laboratories."

The problem is thus two-fold: (1) To determine whether additional tests are needed. And (2), to outline a test program.

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* Numerals in parentheses refer to numbered items in the list of references at the end of this report.

II. NEED FOR ADDITIONAL TESTS

Two criteria are given by which to determine whether additional tests are needed: (1) To verify the theories developed, or (2) to provide a basis for extending them over a sufficiently wide range to make them suitable for use in design.

3. Comparisons with ORDL Culvert Tests

Tests made by the Ohio River Division Laboratories have been reported in Reference 3. It is proper to ask first whether these tests are in themselves sufficient to provide verification of the theories. Although the agreement between the predictions of the theories and the results of the tests was most encouraging, its significance is somewhat reduced by the fact that in many cases it was necessary to make certain assumptions regarding the actual magnitude and distribution of moment in the test specimens. Since the theories are themselves based primarily on assumptions unsupported by adequate experimental evidence, the measure of agreement obtained between tests and theory cannot be considered an adequate verification of the theories or of the assumptions on which they are based. Furthermore, even if the agreement could be accepted as significant for these tests, the scope of the tests was much too limited to justify acceptance of the theories without further study.

4. Other Tests for Flexural Strength

We may ask next whether the theories can be justified on the basis of existing test data from other sources. The theory for strength in combined flexure and axial load was in fact based on existing data from numerous tests of eccentrically loaded columns. In the great majority of these tests, however, the principal emphasis was on members for which the axial load was relatively large as compared to the moment, with the result that failure was in compression. The culvert problem, however, requires consideration of the case in which the moment is relatively large as compared to the axial load, and failure occurs by yielding of the reinforcement. Although some tests have been made on columns for this range of conditions, they have not been sufficiently great in scope to permit a completely satisfactory verification of the theories that have been advanced. One difficulty that has been encountered in this respect arises from the fact that the culvert problem requires the use of the case of pure flexure as a base, whereas most of the existing tests have been interpreted using the case of axial load as a base. The extent to which additional tests are needed to verify the theories for members subjected to axial load and failing in flexure depends in some measure on the philosophy of design adopted and the degree of precision required in the calculation of yield and ultimate moments, but it seems clear that additional tests are needed.

5. Other Tests for Shear Strength

The expressions that have been developed to predict the strength in shear of members subjected to combinations of shear, flexure, and axial load are based on empirical expressions for the shear strength of members without axial load. However, the effect of axial load has been introduced in a manner which is entirely theoretical; no tests having a bearing on this problem were available at the time the theory was developed. Since that time, however, a program of tests to determine the strength in shear of reinforced concrete members without web reinforcement and subjected to shear, axial load, and flexure has been undertaken in the Department of Theoretical and Applied Mechanics at the University of Illinois under the sponsorship of the Reinforced Concrete Research Council. A progress report on these tests was issued in September 1953 (4) but since it has not been released for publication the results obtained are not available for use on this project. These tests are being made on L-shaped members representing the corner element of a frame and thus simulate rather closely the conditions at the column-face section in a culvert. Although the ratio of moment to shear has been varied in these tests, the ratio of axial load to shear has been held constant at a value of one. This is believed to constitute a serious limitation on the applicability of the results to this problem unless, of course, the agreement with the theories that have been developed should be quite good. Another deficiency of these tests, so far as the culvert problem is concerned, is that the percentages of tension reinforcement used have been fairly large, usually much greater than those commonly used in culvert design. Still another limitation is that the results obtained from these tests apply only to the column-face section, that is, to the corner, whereas it seems likely that the strength in shear at some location in the span must also be considered in the design of culverts. It may be concluded, therefore, that additional tests are required in order to verify the applicability of the expressions developed for predicting shear strength.

6. Actual Moments Due to Applied Loads

The calculation of flexural and shear strength, as discussed in the preceding paragraphs, is only one part of the culvert problem; it is necessary to know also the moments and shears produced by the applied loads. In conventional design procedures it is customary first to assume the design loads, and then to compute moments and shears by conventional procedures based on the assumption that the structure behaves elastically. It is not necessary that these moments and shears be known precisely, or even that they be correct, since the working stresses and the methods used for proportioning sections have presumably been selected in such a way as to provide a satisfactory structure. If this objective were always achieved, there would of course be no necessity for this investigation of culvert design and behavior. However, in order to analyze the results of tests, and in order to understand the behavior of culverts and arrive at appropriate design criteria, it is necessary to know the actual magnitudes of the moments in the structure and to be able to predict how and how much they will differ from those computed by an elastic analysis.

For an understanding of the behavior of a culvert under load and in order to predict its load-carrying capacity at various stages, it is necessary to know (1) the total static moment, and (2) the manner in which that moment is distributed between the midspan and column face sections; in some cases it may also be necessary to know the distribution of moment along the span.

Total Static Moment -- The total static moment for a given member is a function of the span length, the total load, and the distribution of the load along the span. Under either design or test conditions it will always be necessary to assume that the total load is known. In design, it is usually assumed that the load is distributed uniformly along the span even though the actual earth pressures can conceivably be distributed non-uniformly. In the ORDL tests a uniform load was simulated (3). It is believed, however, that because of deflection of the horizontal member and the consequent non-uniform deflection of the springs, the load distribution at high loads was no longer uniform. Although the resultant error in the total static moment computed for a uniform load was not great and occurred only at high loads or loads appreciably beyond yielding, the non-uniformity of the load distribution had to be taken into account in the analysis of the tests. This phenomenon was solely a consequence of the test procedure and is discussed here as a guide to the planning of future tests. If behavior beyond yielding is to be investigated, provisions should be made either to insure a uniform distribution of load at all stages of the test or to determine the actual distribution, whatever it may be. Although non-uniform distribution of soil pressures may occur in actual service, and the distribution may change significantly as the load is increased, it is not proposed that these conditions be studied in laboratory tests. Nevertheless, some consideration may have to be given to actual soil pressure distributions in the development of design criteria.

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Redistribution of Moment, Due to Cracking -- The question of distribution of moment between midspan and column-face sections is more significant than the changes in total static moment discussed in the preceding paragraph. This distribution may change markedly as the load on the structure is increased, and the changes can have an appreciable effect on the behavior of the culvert at almost every stage. At low loads, before cracking, the distribution of moment probably corresponds very closely to that computed from an elastic analysis. Under design loads, cracking will have occurred and some changes in relative stiffness may result. In general, if each critical section of the culvert has been proportioned on the same basis, and if the actual loads and moments at each section correspond fairly closely to those used in design, the cracking at each section and the consequent changes in absolute stiffness will be of the same order of magnitude, and the relative stiffnesses of the various sections will remain substantially unchanged. In this case, the distribution of moments will be approximately the same after cracking as before. The conditions necessary to bring about this state of affairs will not always be met in practice, however. For example, a culvert may be designed for a ratio of lateral to vertical unit pressure varying from one-third to two-thirds. The midspan section would than be designed for the maximum positive moment, resulting from the lower ratio, while the column-face section would be designed for the maximum negative moment, resulting from the higher ratio. If the actual ratio of lateral to vertical pressure in service is one-third, the column-face section will be understressed as compared to the midspan section, and differences in cracking and in relative stiffness will result.

Changes in stiffness as a result of unequal cracking have little effect on the ultimate strength of a culvert as measured by either the collapse load or the load producing general yielding, so long as failure is in flexure. These redistributions of moment, however, may have a fairly well defined effect on the load producing first yielding and may be of considerable importance in determining whether initial failure will be in flexure or in shear. The results obtained in the ORDL culvert tests (3) suggest that once yielding has occurred at a given section, failure in shear is no longer possible (2). Since the actual moments at first yielding may differ appreciably from the theoretical "elastic" moments; future tests should be made in such a way that the moments at a given section will be known at all stages of loading and the effects of cracking on the distribution of moment can be determined. Studies should also be made of the possible ranges in design loadings and their relationship to possible service loadings in an attempt to evaluate the range of difference in relative stiffnesses that may be expected. These studies will be partly analytical, but some tests, either independent or incorporated in other parts of the program, will be required.

Redistribution of Moment after Yielding -- Redistribution of moment, after yielding has occurred at one or more locations, is another phenomenon observed in the tests (3) and tentatively explained by the theory (2). This redistribution affects directly the ultimate load-carrying capacity of a culvert and may have some effect on the mode of failure. Since the deformations of the members are also involved, the question of changes in distribution of the load in tests with springs and the consequent changes in total static moment are also involved. Whether these questions are of primary interest depends on the importance attached to ultimate strength or collapse load in design. In any case, future tests should be planned and carried out in such a manner that the actual moments at each section are known or can be determined. At the same time, careful measurements of deformations in any tests carried to failure will yield information on the relation between moments and deformations which is essential to an understanding of the redistribution phenomena after yielding.

7. Summary -- Need for Additional Tests

It may be concluded that additional tests are needed in two categories:

(1) Tests to verify the theories for ultimate strength in flexure and shear as affected by axial load. These tests are fundamental in nature and can most economically and efficiently be made on relatively simple specimens rather than on simulated culverts. The scope of the tests must be sufficient to insure the reliability of the theories or expressions developed over a wide enough range to include the conditions that may exist in typical structures.

(2) Tests to determine the ability of the theories to predict the behavior, strength, and mode of failure of box culverts. These tests should be made on specimens simulating as closely as possible the behavior of actual culverts, and should be carried out in such a manner that the actual behavior of the culvert specimen is known at all stages of the test.

III. NATURE OF TESTS REQUIRED

It has been shown that additional tests are needed in order to provide the information necessary for the development of design criteria for reinforced concrete box culverts. The nature of the tests required is discussed in this chapter. The discussion is divided into three parts:

(a) Strength in combined flexure and axial load.

(b) Strength in combined shear and axial load.

(c) Load-carrying capacity of culverts.

Items (a) and (b) refer to basic tests needed for the development of suitable theories, while (c) refers primarily to tests of simulated culvert models intended to establish the applicability of the theories to culverts.

8. Strength in Combined Flexure and Axial Load

Tests are needed to determine the effect of axial load on the yield and ultimate moments and the corresponding deformations for members similar to those used in culverts and having ratios of axial load to moment similar to those likely to be enountered in practice. Two steps are involved:

First, it will be necessary to make analytical studies based on typical culvert dimensions and loadings to determine the range of variables to be studied, including: ratio of axial load to moment, concrete strength, tension and compression steel percentages, proportions of member, position of casting, etc. The existing theory can then be used to predict the behavior of a variety of members under various conditions within the range determined, and appropriate specimens selected for tests.

The first tests should be made on relatively uncomplicated members subjected to axial load and designed to fail in a region of pure flexure in order that basic data can be obtained. The tests can then be extended to study the flexural behavior in the neighborhood of a beam-column intersection and with shear present, probably by means of tests on simply-supported beams loaded at midspan through a column stub. The variable of uniform load can best be introduced in tests of simulated culvert specimens.

9. Strength in Combined Shear and Axial Load

Tests are required in order to verify the assumptions and resulting theory relating to the strength in shear of members subjected to axial load. As in the case of flexure, it will be necessary first to make preliminary analytical studies based on typical culvert dimensions and loadings in order to establish the range of variables.

Until preliminary analyses or tests prove otherwise it must be assumed that an initial shear failure may occur either at the column face or in the positive moment region. Since the conditions are different at these two locations, different problems are involved and must be treated separately in planning the tests. At the column face, the shear and moment are both a maximum at the same location, whereas the ratio of shear to moment varies from point to point in the midspan region. Another difference arises simply from the presence of the beam-column corner and the possible restraint offered to the concrete at the column face; these restraints are absent, or are present to a much lesser degree, in the positive moment region. The tests proposed to study shear strength are therefore discussed separately for these two sets of conditions.

Shear Strength at Column Face -- Since the effect of axial load has been taken into account by a purely theoretical modification of an empirical expression derived from tests on simple beams, it is first necessary to examine the basis for that expression. The shear strength at a beam-column intersection has been based on an empirical equation derived from only a very limited number of tests on simple-span beams loaded through a column stub at midspan (7). These tests, however, suggested strongly that the strength in shear under these conditions was significantly different than that obtained in tests of beams loaded with two symmetrically located loads. The scope of the tests, however, was not great enough to provide a truly reliable estimate of the shear strength under these conditions, nor did the tests show clearly that the increased strength observed resulted from the presence of the column stub and not from the use of a single load at midspan. Additional tests are required in order to be able to predict the strength in shear even in the absence of axial load. A suitable approach to the question of shear strength at the column face in culverts would involve the following tests:

(1) Tests to determine the effect of a beam-column intersection without axial load in the member. It would be desirable to omit the added variable of uniform load at first and make these tests on simple beams with and without the stub. Next, tests with uniform load could be made on a specimen looking substantially like the beam with a stub column at midspan but loaded uniformly along the beam with the reaction provided at the stub.

(2) Tests to determine the effect of axial load on shear strength at a column face. Again, it would be desirable to eliminate the uniform

load variable at first and to make these tests on simple specimens with known axial loads. Simple beams loaded at midspan through a column stub could be used, and the axial load could be applied either through jacks acting axially on the beam or by means of a tie rod and jack combination acting on brackets extending at right angles from the ends of the beam. In the latter case, additional moments would be introduced with the axial load but their magnitudes would be known. For a study of the effect of uniform loading, the second type of specimen with brackets would have certain advantages since the brackets themselves could represent the columns and the stub at midspan could thereby be omitted.

If the results obtained in the tests without uniform loading are in sufficiently good agreement with the theories and no new questions are raised, it may be possible to introduce the uniform load condition only in the tests on simulated culvert specimens.

Shear Strength in Positive Moment Region -- In this case, the principal problem is to determine the critical location for failure in shear since both the shear and the moment vary from point to point. Extremely limited experimental evidence has suggested that shear failure occurs when the limiting shear-moment is reached at a section of the beam at which the M/Vd ratio has a particular value. Laupa (1) has suggested that M/Vd must be not greater than about 4.5, and this value has been used in the analysis of the ORDL culvert tests. The evidence in support of this value is so meager, however, that additional tests are undoubtedly necessary. For the culvert problem, it is necessary to know the conditions for shear failure in a uniformly loaded member subjected to shear, axial load, and flexure. It would seem desirable, however, to approach this problem in steps, beginning with a limited number of variables and increasing the complexity of the tests as additional understanding is obtained. A tentative program of tests would include the following:

(1) Tests to determine the effect of the M/Vd ratio on the behavior and strength in shear of simple beams loaded with two symmetrically placed concentrated loads. Theoretically, the effect of M/Vd as determined from such tests will provide data for locating the critical section in uniformly loaded beams. These tests are proposed first since they involve only very simple specimens and test procedures.

(2) Extension of tests in (1) to include axial load, and its effect on the critical M/Vd ratio. The effects of axial load in reducing diagonal tension and delaying cracking may be of considerable importance.

(3) Tests of uniformly loaded beams without axial loads, since axial load may not always be present in culvert members.

(4) Tests of uniformly loaded beams with known axial loads. At this point it may be desirable to introduce restrained beams or beam-column assemblies in order to simulate more closely the conditions in a culvert. Also, it may be desirable to investigate the effect of M/Vd on the shear strength and failure criteria at the column face, unless the previous test results and analyses indicate that such a study is not needed.

Shear Strength After Flexural Yielding -- The studies made so far have raised the important question of whether shear failures can occur at a given location after yielding has occurred at or near that location. Tests on simple beams have yielded little information on this problem since little increase in load, and thus in shear, can occur after yielding. However, if axial load is present and increases with the load, it is possible to increase the load and shear appreciably after yielding has occurred. Similarly, in an indeterminate structure, redistribution of moments permits an increase in load and shear after yielding. Two types of tests are indicated:

(1) Tests of restrained beams without axial load. The axial load is eliminated partly in order to simplify the test procedure but also because it may not always be present in culverts.

(2) Tests of restrained beams with axial load.

However, it may be possible and preferable to study this phase of the problem by means of tests on simulated culvert sections rather than restrained beams.

10. Load-Carrying Capacity of Culverts

The tests discussed in the foregoing paragraphs are all basic. They are needed to provide checks on the existing theories or to develop new theories for predicting the behavior, strength, and mode of failure of culverts. Once the basic data have been obtained, the theories can be refined or corrected and thus be made available for application to the more complex problem of the culvert itself. At this stage, tests should be made on structures representative of actual or typical culverts and the results compared with the predictions of the theories.

For these tests, the closed frame as used by the ORDL provides an excellent model of a culvert but at the same time has certain disadvantages, the most serious of which is the lack of complete knowledge regarding the magnitudes of the moments, shears, and axial loads. It is suggested, therefore, that the tests in this phase of the work be made on open frames consisting only of a horizontal member and two vertical legs. Axial loads in the horizontal member and restraining moments at its ends can be provided by applying horizontal reactions at the bottom of the vertical legs. These reactions can be both controlled and measured, and if the applied vertical load is known both in distribution and magnitude all forces acting on the members will be known or can be determined from statics.

Tests on specimens of the type described in the preceding paragraph will provide the final data needed to predict the moments due to the applied loads at any stage in the test. The final stage of this investigation can then include tests on closed frames typical of culverts designed according to various criteria. These tests will provide a final check on our ability to predict the behavior, strength, and mode of failure of culverts, and will provide the best possible basis for the selection of design criteria.

IV. OUTLINE OF PROPOSED TEST PROGRAM

11. Outline of Tests

The need for additional tests has been discussed in Chapter II, and the general nature of the tests required has been outlined in Chapter III. The scope of the proposed program is indicated by the outline in Table 1. The two main categories, A. Tests of Structural Members, and B. Tests of Culverts, correspond to those discussed in Section 7 of Chapter II. The tests of members have been divided into three main groups corresponding in general to those discussed in Chapter III. Each of these main groups has been further subdivided into series of tests involving a particular type of specimen or loading condition, and concerned with a single phase of the overall problem.

Each series of tests listed in Table 1 is discussed in more detail in the following sections of this report. The object of the tests and the variables to be considered are discussed, and the type of test specimen to be used is indicated by reference to Fig. 1.

12. Combined Flexure and Axial Load -- General (A.1)

The object of this group of tests is to determine the behavior of reinforced concrete members subjected to both flexure and axial load. The term behavior includes the following: initiation and development of cracks in the concrete; the load or moment causing first yielding of the reinforcement; the loads or moment causing ultimate failure of the member through crushing of the concrete in compression; and the load-deformation characteristics at all stages -- before cracking, between cracking and yield, and after yield up to ultimate load.

The principal variables are (1) the ratio of moment to axial load, and (2) the properties of the cross-section of the member. The ratio of moment to axial load should be varied over a range representative of that which may exist in actual culverts. In general, however, the ratio of moment to axial load will be fairly high and most specimens corresponding to culvert members should fail initially by yielding of the reinforcement rather than by crushing of the concrete; that is, failure should be in tension, not in compression. The significant properties of the cross-section include 1) concrete strength, 2) amount of reinforcement, and 3) strength of reinforcement. The presence of compression reinforcement must also be considered.

The individual phases of this group of tests are discussed in further detail in the following sections.

13. Flexure and Axial Load -- Analytical Studies (A.1.1)

The primary purpose of these studies is to obtain information which will be of aid in selecting the ranges of variables for the test specimens.

One variable is the ratio of moment to axial load. In culverts, this ratio will depend on the ratio of height to width of the culvert cross-section and on the ratio of lateral to vertical load intensity. These studies should be concerned with the vertical as well as the horizontal members of a culvert.

Studies should also be made to determine the ranges of concrete strength, percentages of both tension and compression reinforcement, and strengths of reinforcement, as well as the relationships between these variables, if any.

When ranges of typical values have been determined for the variables listed above, it might be desirable to make analyses according to the methods given in Reference 2 in order to determine whether failure of typical members will always be initially in tension or whether under certain conditions initial compression failures may be possible.

The analytical studies discussed in this section should preferably be made before any tests are undertaken. However, it should be possible to plan the first few tests under item A.1.2 in Table 1 before the analytical studies are completed.

14. Flexure and Axial Load -- Third-Point Loading (A.1.2)

The object of these tests will be to determine the effect of axial load on the behavior of a reinforced concrete member subjected to pure flexure over a considerable portion of its length. Although shear as well as flexure will be present in culvert members, tests made in the absence of shear are desirable in order to avoid complications due to too many variables. In general, all of the proposed tests have been planned in such a manner that the several variables involved are introduced one at a time.

Beam-type specimens, simply-supported at their ends and loaded at their third-points, as shown in Fig. 1(a), will probably be satisfactory for these tests. Axial load can be applied by means of springs or hydraulic jacks. The outer thirds of the span should be reinforced with stirrups if necessary in order to prevent shear failures.

The principal variables will be the ratio of moment to axial load and the properties of the cross-section. For each group of specimens having the same section properties, tests should be made with varying magnitudes of axial load, in order to obtain experimentally interaction diagrams of the type shown in Fig. 6 of Reference 2. At least one specimen of each type should be tested without axial load, and it may be desirable that at least one specimen be tested with an axial load such that failure will be balanced between tension and compression; that is, yielding of the reinforcement and crushing of the concrete occur simultaneously.

Whether compression reinforcement is to be provided, and if so, how much, can be decided only on the basis of the preliminary analytical studies. Analyses of typical sections should show whether the effect of compression reinforcement is likely to be important.

Another variable that should be included in these tests is the position of casting. Most of the specimens should be cast and tested with their long axis horizontal. However, at least a few of the tests should be made on specimens cast vertically. These specimens should be similar in all other respects to selected specimens cast horizontally.

Since a tentative theory for the behavior of members with axial load and flexure has been presented in Reference (2), it is not necessary to attempt to answer all of the questions involved in this problem solely by means of the tests. The first tests should be made on fairly typical members with a full range of variation in axial load from zero to that producing balanced failure. The results of these tests can then be compared with the theory. If the agreement is good, additional tests are needed only as spot checks and to investigate the effects of other variables such as position of casting, compression reinforcement, sustained loading, etc.

Recommendations regarding the size of the test specimens, the manner of conducting the tests, and the measurements to be made are contained in a subsequent portion of this report.

15. Flexure and Axial Load -- Concentrated Load (A.1.3)

The tests in this series differ from those in Series A.1.2 in that flexure is produced by a concentrated load at midspan as shown in Fig. 1(b) rather than by two loads at the third-points. Failure in flexure will therefore occur in a region of varying moment as will be the case adjacent to the corner of a culvert. Other investigations have shown that the flexural behavior of a member without axial load may be significantly different when loaded at midspan (5) than when loaded in such a manner as to produce failure in a region of constant moment (6). The object of these tests is to investigate the differences in behavior for these two types of loading in the presence of axial load.

An added variable in these tests is the presence of shear at the location at which failure in flexure is desired. The use of stirrups to prevent shear failures might produce added complications because of their effects in confining the concrete in the compression zone (See Reference 5). On the other hand, this series of tests is tied in very closely with the tests of Series A.2.3.1, and it might be possible to plan these as one series and investigate a range of behavior including both shear and flexural failures. If this is to be done, however, detailed planning for these tests probably should not be attempted until the work has been completed on Series A.2.2.1 and on A.3.2.1 and A.3.3.1, since the results from those tests will permit much more intelligent and economical planning of the tests under consideration.

In any event, the tests in Series A.1.3 should be tied in very closely with those in Series A.1.2 with two-point loading. That is, specimens with the same cross-sectional properties should be used, the only variable being the arrangement of the loads.

In Fig. 1(b), the specimen for these tests has been shown with the load applied through an integrally cast column stub. This is tentatively suggested in order to simulate more closely the conditions at a corner. However, the studies reported in Reference 5 suggest that the presence or absence of the stub may make little difference. If a similar conclusion is reached as a result of the proposed tests of Series A.2.2.1 and A.2.2.2, it may be possible to eliminate the column stub in at least some of the specimens. This would be especially helpful if it should be decided to cast some of the specimens in Series A.1.3 in the vertical position.

16. Shear at Column Face Section -- Analytical Studies (A.2.1)

The analytical studies relating to this group of tests have two principal objectives: (1) to determine the range of variables to be considered in the tests, and (2) to review the tests made by other investigators and to compare the results of those tests with the theories advanced in Reference 2 and with the results of tests made in this investigation.

Studies to determine the range of variables are essentially the same as those discussed in Section 13 in connection with item A.1.1. However, consideration should be given here to the ratios of moment to shear as well as the ratios of moment to axial load.

Some data similar to that which will be obtained in the tests of Series A.2.2.1 and A.2.3.1 have been obtained in the investigation mentioned in Section 5 and have been reported informally and unofficially in Reference 4. These tests are continuing and it is to be expected that published reports will be available before the tests proposed herein have been completed. The results of these tests as well as any theoretical interpretations offered should be studied and compared with the theories advanced in Reference 2 and with the results of the proposed tests as they become available. Only in this way can needless duplication of effort be avoided. However, it must be realized that it may be possible to use the results from other investigations only as supplementary or confirming evidence rather than a substitute for the proposed tests.

It should be pointed out that these analytical studies are not intended to serve solely as a basis for planning the test program. This item in Table 1 is intended rather to represent a phase of the program which will extend throughout the test period and will play an important part in interpreting the results and evaluating their significance. As new phenomena are observed in the tests, it may be necessary to re-evaluate the range of variables. Furthermore, only by continually comparing the results of the tests with theories already advanced or with new theories can the success of the investigations be assured.

17. Shear at Column Face Section -- Tests Without Axial Load (A.2.2)

Tests without axial loads are required 1) because axial load may not always be present, and 2) in order to investigate initially what is in itself a fairly complex problem. These tests are subdivided into three series as indicated in Table 1 and as shown in Fig. 1(c), (d), and (e).

Series A.2.2.1 -- With relatively few exceptions (4) knowledge regarding strength in shear is derived from tests on beams loaded with two symmetrically placed concentrated loads, a condition which is significantly different from that existing at the corner of a culvert; that is, at what has been called the "column-face section" when referring to the horizontal member of a culvert. The tests of beams loaded at midspan through a column stub (7) yielded strengths in shear significantly greater than previous tests under two-point loading (1). However, the tests that have been made with midspan loading are so few in number that further investigation is required. This then is the objective of the tests denoted as Series A.2.2.1 in Table 1 and indicated in Fig. 1(c).

The tests reported previously by Laupa (7) may be used as the basis and background for this series. The tests reported in Reference 4 or in subsequent reports on that project may also be utilized if they have been published or released for publication. In any case, the tests must be extended to include members with compression reinforcement and to provide additional data as a check on the relations previously established on the basis of only nine tests.

Series A.2.2.2 -- A question may be raised as to whether the increased shear strength of beams loaded at midspan through a column stub

(Fig. 1c) results from the presence of the column stub, from the nature of the single-point loading, or from restraint that may be offered to the concrete beneath the load point. It is proposed, therefore, that a few tests be made in which the beams are loaded at midspan through a steel bearing plate such as might be used in applying load in tests of culverts. The specimens to be tested should be similar in properties to selected specimens from Series A.2.2.1. However, unless unforeseen complications arise, it should be necessary to test only a small number of beams. If loading through a steel bearing plate produces the same increase in shearing strength as loading through a column stub, it will still be necessary to determine whether the effect is that of midspan loading or restraint offered by the vertical load. However, this question can probably be answered by comparisons between the results of this series (A.2.2.2) and Series A.3.2.2 with uniform load.

Series A.2.2.3 -- The object of these tests is to determine the effects of uniform loading on the strength in shear adjacent to a beam-column intersection. The concept of shear failure developed and presented in References (7) and (1) involves failure at a limiting moment; however, failure in this manner depends on the development of inclined cracks as the result of stresses due shear as well as moment. In specimens loaded as shown in Fig. 1(c) and (d), the shear is constant over the portion of the member adjacent to the location at which the moment is a maximum. With uniform loading, the shear may decrease rapidly with distance from the point of maximum moment and the formation of inclined cracks at the critical section may be delayed or prevented with the result that failure could be in flexure rather than shear. The tests of

Series A.2.2.3, on specimens loaded as shown in Fig. 1(c) are intended to provide a better understanding of these phenomena. As in the case of Series A.2.2.2, extensive tests are not needed; only a few specimens, having properties similar to those used in Series A.2.2.1, need be tested. The dimensions of the specimens will have to be chosen in such a manner that the ratios of moment to shear at the critical section bear the desired relation to the corresponding ratios in Series A.2.2.1. This relation, however, cannot be determined in advance and must be selected on the basis of the results obtained in Series A.2.2.1 and possibly only after pilot tests are made in Series A.2.2.3.

18. Shear at Column Face Section -- Tests with Axial Load (A.2.3)

The tests in this group are divided into two series as indicated in Table 1 and Fig. 1(f) and (g).

Series A.2.3.1 -- The tests of this series are intended to investigate the effects of axial load on the strength in shear. The loading arrangement shown in Fig. 1(f) is the same as that in Fig. 1(c) except that axial load has been added. Also, as has been noted previously, the loading in Fig. 1(f) is identical with that in Fig. 1(b) for Series A.1.3. The tests of Series A.2.3.1 should be planned as a check on the theories advanced in Reference 2, Section 10. A group of similar specimens should be tested under increasing values of axial load and the results compared with those obtained from the theory. If the agreement is good, additional tests may be limited to spot checks for the effects of other variables. On the other hand, if satisfactory agreement with the theory is not obtained, a fairly extensive series of tests incorporating all of the variables over a considerable range will have to be undertaken.

The possibility of combining the tests of Series A.2.3.1 with those of Series A.1.3 has been mentioned previously as a means of studying the transition from shear to flexure failure.

Series A.2.3.2 -- The object here is to determine whether the effect of uniform loading is modified by the presence of axial load, and vice versa. If little effect of uniform load has been noted in Series A.2.2.3, and if the effect of axial load is as small as suggested by the theory, it may be possible to eliminate these tests altogether. However, the complexity of the problem and the uncertainties regarding how the various effects interact, probably requires that at least a few tests be made under the conditions shown in Fig. 1(g) before this type of loading is encountered in tests of culverts.

19. Shear in Positive Moment Region -- Analytical Studies (A.3.1)

The object of these analytical studies is essentially the same as those discussed in Section 16, and again they should represent not only a planning stage but a continuing effort to interpret and compare the results with the available theories or hypotheses and with other tests.

20. Shear in Positive Moment Region -- Tests Without Axial Load (A.3.2)

All of the tests proposed in Group A.3 have as their immediate objective the verification of the hypothesis advanced in Reference 1, Sections 20 and 21 regarding the critical value of M/Vd for failure in shear. This critical ratio of M/Vd is of considerable importance in connection with the formation of inclined cracks, the conditions under which shear failures will occur, and the location at which shear failures will occur in members subjected to distributed loads. These tests are basic to any study of shear strength, and apply not only to the positive moment region but also in some measure to the column-face section.

Again it has been recommended that tests be made first without axial load in order to avoid undue complications and in order to simplify test procedures. Two series of tests without axial load are planned, to be followed by parallel series of tests with axial load.

Series A.3.2.1 -- These tests would be made on simple beams loaded with two loads symmetrically placed about midspan but not necessarily at the third points, as shown in Fig. 1(h). The principal variable will be the ratio M/Vd or a/d, where a is the distance from a load to the nearest support and d is the effective depth of the beam. The ratio a/d should be varied from a value low enough to cause failure in shear to a value high enough to cause failure in flexure. In this manner the critical value of a/d can be found. Other variables should include the properties of the beam cross-section in order to determine whether the critical value of a/d or M/Vd depends on these properties.

Series A.3.2.2 -- The loading arrangement for these tests is shown in Fig. 1(i) and consists of a uniformly-loaded simple beam. Detailed plans for these tests cannot be made until the results of Series A.3.2.1 are available, but the object will be to test beams having properties similar to those of the beams in Series A.3.2.1 and to determine whether failure in shear occurs at locations for which the value of M/Vd is comparable to that found from the previous tests. It is possible that some variations in span length, loading arrangement, bearing blocks, load spacing, etc. may have to be studied also in these tests.

21. Shear in Positive Moment Region -- Tests with Axial Load (A.3.3)

Series A.3.3.1, with two loads, and Series A.3.3.2, with uniform load, are similar to the two test series in group A.3.2 but with axial load added as shown in Fig. 1(j) and (k). The object of these tests is to determine the effects of axial load on the critical value of M/Vd at which the transition from shear to flexure failure takes place. Needless to say, these tests are basic to the entire problem of shear in culverts and are especially important in connection with the initiation and development of cracks. However, if generally consistent results are obtained in the tests without axial load it may be possible to reduce the number of tests in this group, especially those tests with uniform load.

22. Order of Testing in Group A

The tests of each series under the heading "A. Tests of Structur-Members" in Table 1 have been discussed in the preceding sections of this report in the order in which they appear in the table. However, in order that each series of tests may be planned in view of the information ovtained in previous tests, it is suggested that the order of testing be different from that listed in Table 1. It is tentatively recommended, therefore, that the tests be made in the following sequence.

Series A.1.2

Series A.2.1, A.2.2, and A.2.3

Series A.3.2.1, A.3.2.2, A.3.3.1, and A.3.3.2

Series A.1.3 and A.2.3.1

Series A.2.3.2

The analytical phases of the investigation, A.1.1, A.2.1, and A.3.1 must of course be undertaken at the appropriate times in order to furnish data for the planning of the tests.

23. Tests of Culverts (B)

At the conclusion of the tests listed under "A" in Table 1, sufficient data should be available to predict the behavior of reinforced concrete members under conditions of loading and restraint similar to those found in culverts. Theories of behavior, not only of members but also of culverts, can then be developed. These theories must then be checked against the results of tests on culverts or on assemblies of members simulating culverts as discussed previously in Section 10 of this report.

It is recommended that tests be made first on specimens similar to that shown in Fig. 2. The horizontal member of this specimen is subjected to the same loads and restraints as the corresponding member of a culvert. However, the use of a tie rod to provide the horizontal reaction provides a means of both controlling and measuring the horizontal force and thus both the axial load and end moment for the horizontal member. Thus all moments, shears, and thrusts acting on the member are known at all stages of the test, and comparisons with the results of analyses or with the results from the tests on individual members is facilitated.

As a final step in this investigation, tests can be made on closed frames representative of the cross-sections of typical culverts. These tests will involve additional variables associated with changes in the stiffness of the members due to cracking or yielding and the effects of these can be studied.

It may also be desirable to test either simulated culvert sections or closed frames under sustained loads, but proposals for tests of this nature cannot be made in the light of present knowledge.

V. TEST PROCEDURES

This chapter contains recommendations regarding such features of the tests as size of test specimen, control tests of materials, loading, measurements, and other observations. Recommendations are made only in general terms; the exact procedure to be followed in any particular case will depend on the objective and nature of the tests in question as well as on the experience gained and difficulties enountered in previous tests.

24. Size of Test Specimens

Several considerations enter into the choice of the size of test specimens. These include:

(a) The load-capacity of the testing machine to be used.

(b) The physical dimensions of the testing machines.

(c) The facilities available for mixing and placing concrete.

(d) The space available for storing and curing specimens.

(e) The requirement that the specimens be representative of members or structures used in practice.

Items (a) through (d) in the above list usually set an upper limit on the size of the specimen while item (e) which is of primary importance imposes a lower limit. It is essential that the test specimens be large enough that concrete with coarse aggregate of at least 3/4-in. maximum size can be used and that not less than two No. 3 deformed reinforcing bars will be required in the specimens having the smallest percentage of reinforcement. The No. 3 bar is the smallest size that can be obtained with normal deformations meeting the requirements of ASTM Designation A-305.

For the tests of beams, a specimen having a cross-section 6-in. wide by about 12-in. overall depth has been found satisfactory in previous tests (5) (6) (7). Some consideration should also be given to the use of a cross-section having a width greater than the depth, since the specimens are intended to be representative of slices cut from a slab or wall. This shape of cross-section, however, has certain disadvantages. The depth of the member should be similar to that for typical culvert designs, and in some cases, the required width might be so great as to require three or four reinforcing bars in order to avoid large bar spacings or the use of large diameter bars. This is objectionable principally because of the need in certain of the tests to measure strains in all of the reinforcement present. If more than two bars are required, the number of strain measurements will be increased considerably, and the interpretation of the tests will be made more difficult.

It is tentatively recommended, therefore, that consideration be given to the use of beam-type specimens having a cross-section of about 6 by 12 in. However, studies should be made to determine typical values for the depths of members in culverts.

In the tests of simulated culvert sections, it might be advisable to use wide sections in order to provide a more stable test set-up.

25. Curing

It is suggested that all test specimens be cured either in a fog room or under wet burlap for seven days and after that allowed to dry out in the air of the Laboratory. If this procedure is followed, the behavior of the specimens in the tests is relatively insensitive to the age at test, provided that they are at least 28 days old, and greater latitude in the test schedule is thereby attained.

26. Control Tests

Concrete -- One of the most important properties affecting the strength in shear is the compressive strength of the concrete. At least three, and preferably five, standard 6 by 12-in. test cylinders should be made from each batch of concrete placed in each test specimen. These cylinders should be placed in the molds and cured and stored under the same conditions as the test specimens. At the time the specimen is tested, the control cylinders should be tested in compression and values of the compressive strength and of the initial tangent modulus of elasticity obtained.

If more than one batch of concrete is required for each specimen, the location of each batch should be recorded. Consideration should be given to the locations of the critical sections of the specimens when deciding where the various batches are to be placed.

Reinforcing Steel -- It is usually helpful in planning a test series and in designing test specimens to know in advance the yield strength of the reinforcement to be used. Since yield strength varies appreciably from lot to lot as well as with size of bar, it is recommended that tension tests be made on a short length of each bar used in these tests. It would be desirable to make such tests as the bars are received so that the needed information will be available when the tests are planned.

For specimens failing in shear, the properties of the reinforcement are of secondary importance since the steel stress at failure should be below the yield point. However, for flexural failures or for balanced or nearly balanced failures, the properties of the steel may have a significant effect on the behavior. It is desirable, therefore, that stress-strain curves be obtained and that these be carried at least into the early portions of the work-hardening region. This information may not be needed in all cases and tests of this nature may not be required for each bar; nevertheless, it is essential that at least the yield point be known for each bar used.

27. Loading

The concentrated lateral loads such as those in Series A.1.2 and A.1.3 (Fig. 1a and 1b) present no particular problem since they can be applied by a conventional testing machine and measured by the weighing system with which the machine is equipped.

Distributed lateral loads like those in Series A.2.2.3 or A.3.2.2 may be applied by means of calibrated springs or calibrated hydraulic jacks. If springs are used, their deflections should be measured in such a manner that the magnitude and distribution of the load is known at all stages of the test up to failure. If hydraulic jacks are used, they should be calibrated in order to correct for the effects of friction and, if possible, the test set-up should insure that the rams in all jacks are moving in the same direction at all stages of the test.

The axial load may be applied by means of either springs or hydraulic jacks with reaction supplied by tie-rods connecting the two ends of the beam. Because of the danger of buckling of a deflected axially-loaded member, the use of hydraulic jacks would seem preferable to springs.

28. Measurements

Deflections: Deflections should be measured in all tests, at least at midspan and probably also at other points along the span, depending on the type of loading. Since load-deflection diagrams give an excellent overall picture of the behavior of a member, and since deflections are easily measured, frequent observations of deflection should be made at all stages of the tests up to failure. It is usually desirable to observe loads and deflections at more frequent intervals than strains.

Strains in Reinforcement -- Strains in the reinforcement are of interest in all of the proposed tests. Since the exact locations at which strains should be measured will depend on the expected mode and location of the failures, numerous measurements will have to be made in the first tests and the number decreased as additional experience is gained. Strains should be measured on all bars at a given section, compression as well as tension reinforcement. Strains in the tension reinforcement may be measured with electric wire resistance gages or with portable mechanical strain gages, and the bar may be exposed for the attachment or insertion of the gages. However, since no concrete should be removed on the compression side of a member, strains in the compression reinforcement will have to be measured by means of electrical gages attached to the bars and waterproofed before the concrete is placed.

Strains in Concrete -- Strains should be measured on the top or compression side of the member in the region where failure is expected to occur in order to obtain data on the maximum strains in the concrete at crushing and to provide data from which the location of the neutral axis can be determined. For the purpose of locating the neutral axis, it may also be desirable in some cases to measure strains in the concrete on the sides of the members at various distances from the top surface. Concrete strains can most conveniently be measured with electric wire resistance gages. Type A-9 SR-4 gages with a length of six inches are preferred for determinations of the position of the neutral axis. However, shorter gage lengths are required in regions of rapidly changing stress or at locations where local crushing is to be expected.

29. Crack Formation

The formation and development of cracks is one of the most significant features of a test. After each increment of load and at any significant change in the behavior or appearance of the specimen, the cracks should be noted and marked and a graphical record made of their locations and extent. If possible, photographs should be taken at suitable intervals to provide a record of the appearance of the specimen and the development of cracks. Photographs should also be made to record the appearance of the specimen at failure or at the end of the test.

In addition to observations of cracking and photographs of the specimen, a written record should be kept of any significant changes in appearance or behavior throughout the test, and the manner of failure should be described in as much detail as possible.

VI. SUMMARY

In conformity with the objectives of Stage 5, the test data and analytical studies relating to the behavior and strength of culverts were re-examined to determine whether or not additional tests are needed. It was concluded that additional tests are needed in two categories: (1) Tests of reinforced concrete structural members to provide data with which to verify, correct, or extend the present theories for ultimate strength of members subjected to combinations of flexure, shear, and axial load. (2) Tests on simulated culvert specimens to check the ability of these theories to predict the behavior of reinforced concrete box culverts.

A suggested program of tests has been presented in outline form, and the tests of each series have been discussed in as much detail as is possible at this stage. The tests of structural members have been divided into three main groups concerned with the behavior and strength of members under the following combinations of loading or stress: (1) combined flexure and axial load, (2) combined shear and axial load at the column-face section, and (3) combined shear and axial load in the positive moment region of members carrying uniformly distributed loads. This grouping does not imply, however, that the tests in one group must be independent of those in the other groups. On the contrary, the need to consider the case of combined flexure, shear, and axial load and the transition from flexure to shear failure may require a considerable amount of coordination between the tests in the various groups.

Little detail has been given concerning the tests on simulated culvert sections. These tests cannot be outlined or planned in detail until the tests on structural members have been completed and the results analyzed and interpreted.

In closing, it seems desirable to point out that the box culvert subjected to vertical and lateral loads is as complicated a structure as any constructed of reinforced concrete. For this reason, the scope of the tests needed to provide a complete picture of its behavior is relatively large. At the same time, however, it is important to realize that the information and understanding obtained from the test program proposed in this report will have a value far beyond that associated with the culvert problem alone. The data obtained will be applicable to almost any type of framed structure in reinforced concrete.

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TABLE 1

OUTLINE OF TESTS

A. TESTS OF STRUCTURAL MEMBERS

1. Combined Flexure and Axial Load

    1.1 Analytical studies to determine range of variables
    1.2 Members with third-point loading and axial load
    1.3 Members with concentrated load and axial load

2. Shear at Column Face Section

    2.1 Analytical studies
    2.2 Tests without axial load
        2.2.1 Concentrated load applied through column stub
        2.2.2 Concentrated load but without column stub
        2.2.3 Uniform load with reaction supplied through column stub
    2.3 Tests with axial load
        2.3.1 Concentrated load applied through column stub
        2.3.2 Uniform load

3. Shear in Positive Moment Region

    3.1 Analytical studies
    3.2 Tests without axial load
        3.2.1 Two-point loading with varying span length
        3.2.2 Uniform load
    3.3 Tests with axial load
        3.3.1 Third-point loading with varying span length
        3.3.2 Uniform load

B. TESTS OF CULVERTS

1. Tests on simulated culvert sections consisting of two-legged bents with a controlled horizontal reaction

2. Tests on closed frames representative of actual culvert cross-sections

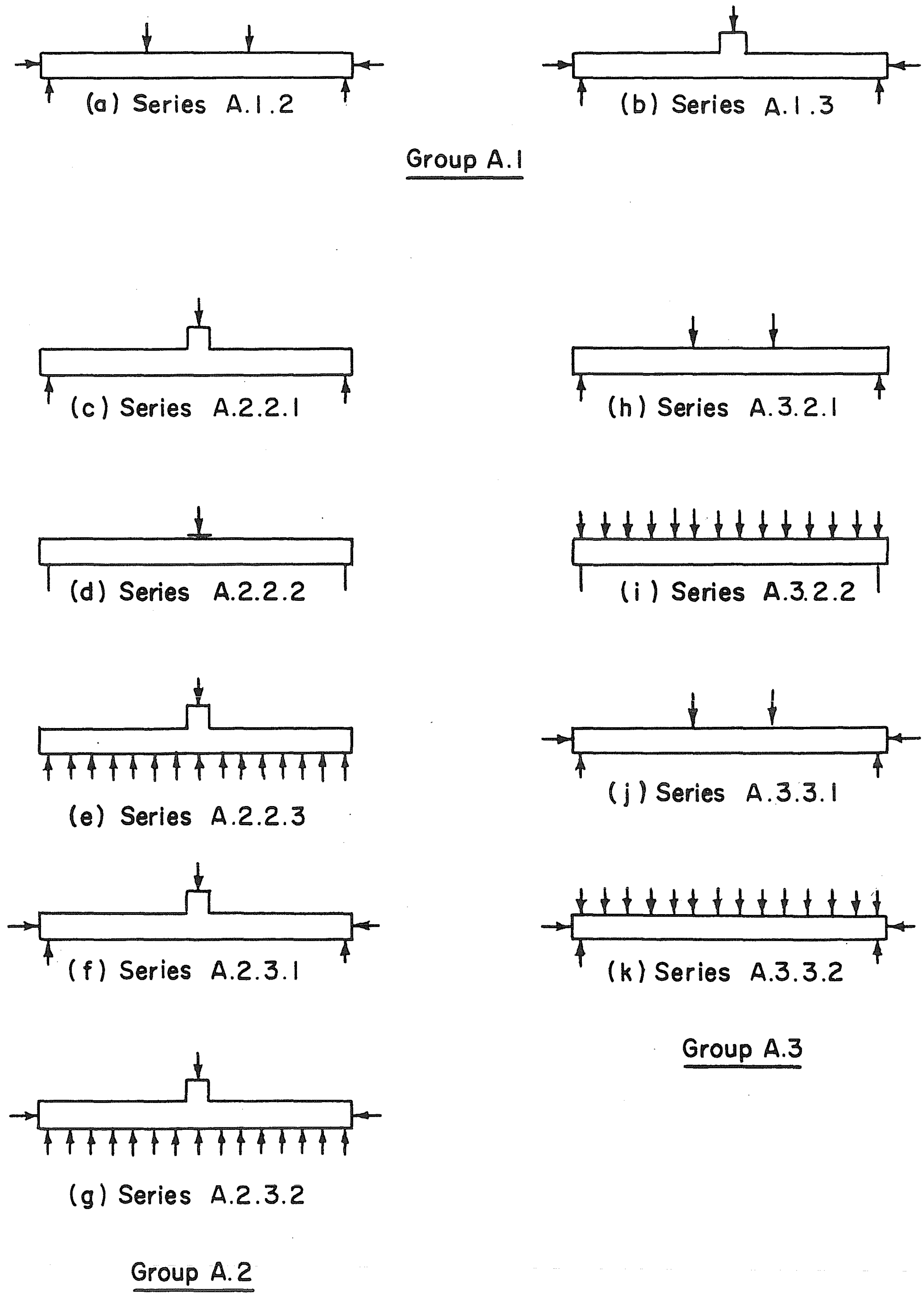

FIG.1. LOADING ARRANGEMENTS FOR TESTS OF STRUCTURAL MEMBERS

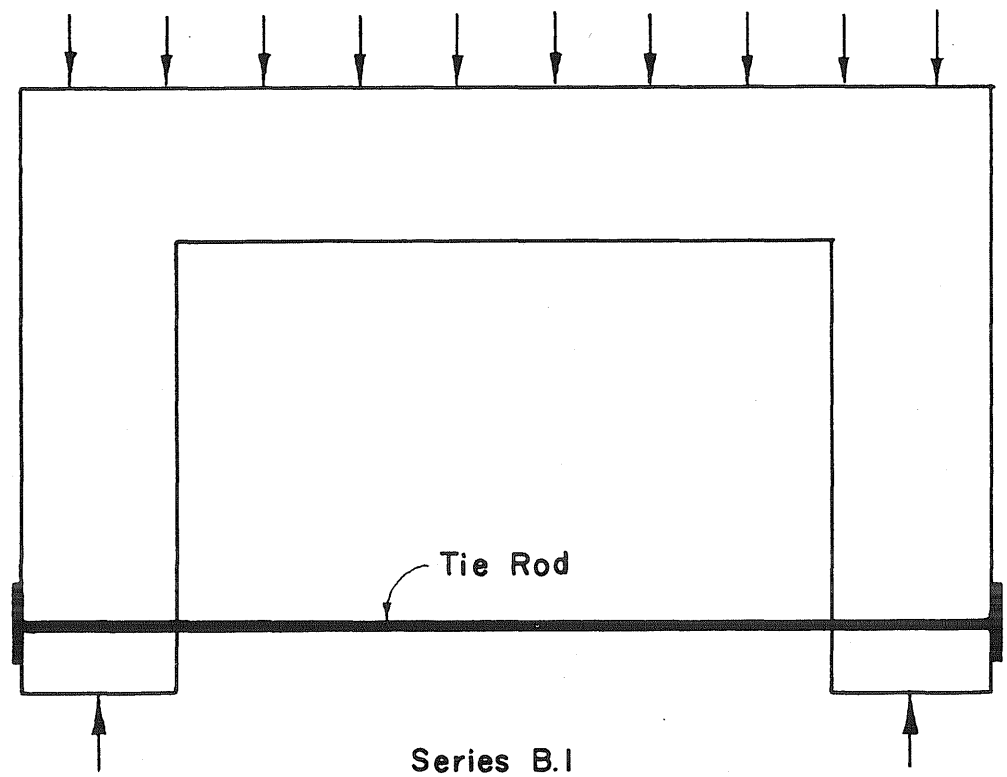

FIG. 2. TYPE OF SPECIMEN PROPOSED FOR TESTS OF SIMULATED CULVERT SECTIONS