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STRUCTURAL SYSTEMS IN SUPPORT OF SAFETY: NEW HIGHWAY STRUCTURES DESIGN CONCEPTS. VOLUME I. RESEARCH INFORMATION

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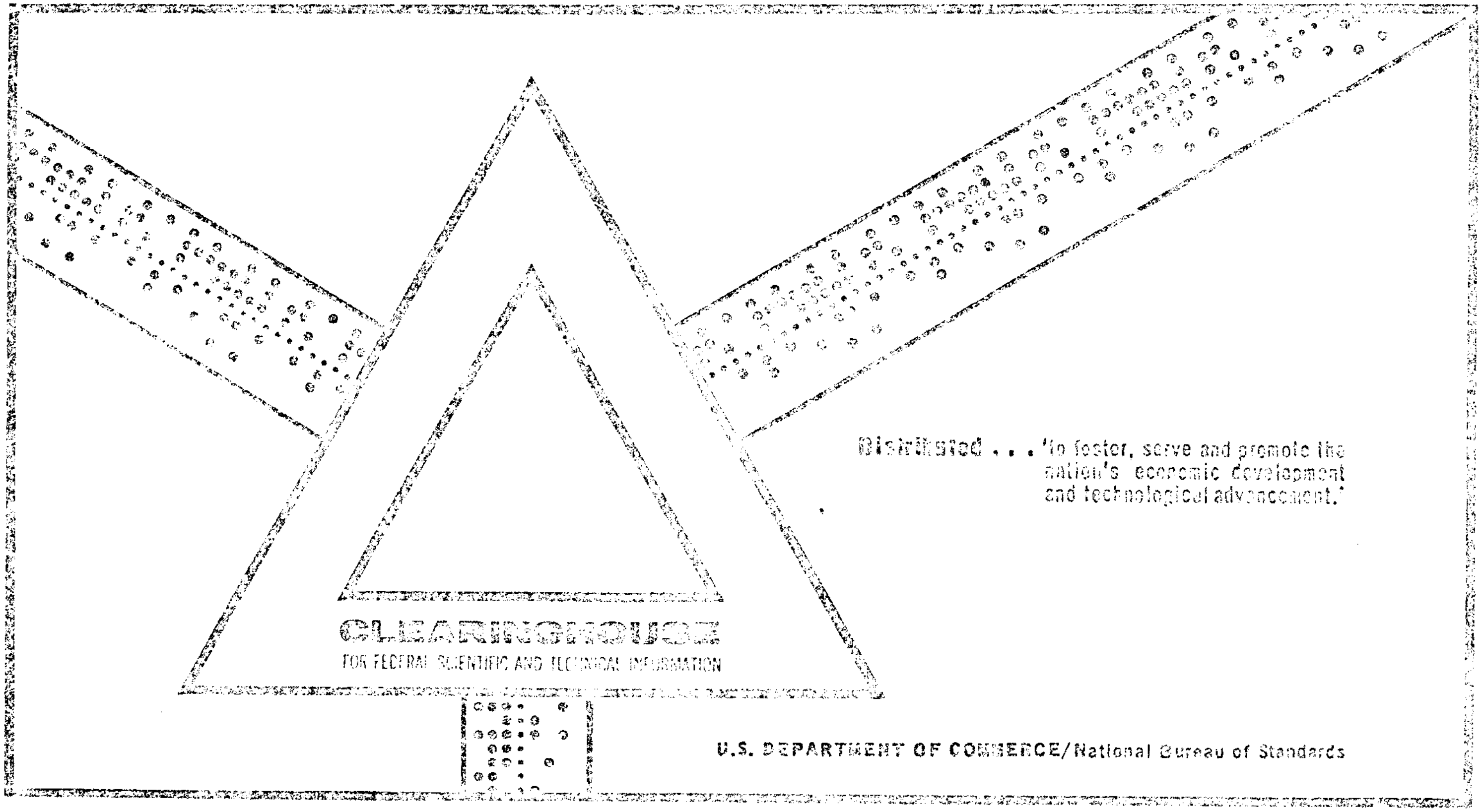
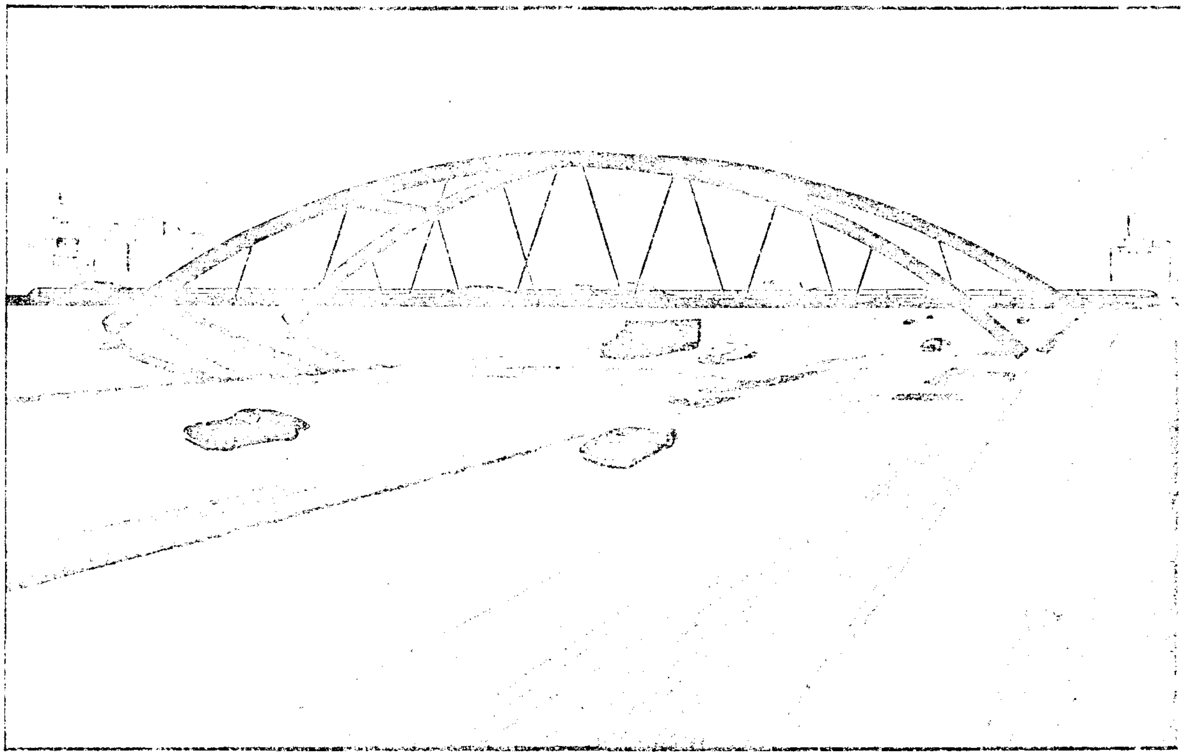
San Antonio, Texas

September 1969





NEW STRUCTURES CONCEPTS FOR HIGHWAY SAFETY

VOLUME I: RESEARCH INFORMATION

STRUCTURAL SYSTEMS IN SUPPORT OF SAFETY: NEW HIGHWAY STRUCTURES DESIGN CONCEPTS

FINAL REPORT
SwRI Project No. 03-2173

VOLUME I. RESEARCH INFORMATION

Prepared under
Contract FH-11-6638
for
The Bureau of Public Roads
Federal Highway Administration
Department of Transportation

September 1969

FOREWORD

The investigation reported herein was conducted by Southwest Research Institute in the Department of Structural Research. Joseph E. Minor and Maurice E. Bronstad served as the project Principal Investigators. This report was prepared under Contract No. FH-11-6638 with the Bureau of Public Roads, Federal Highway Administration, Department of Transportation. The scope of work required development of imaginative concepts for highway structures which are responsive to new safety requirements; however, it was specified that these concepts be limited to structural schemes employing structural cable systems in applications which differ from those used in conventional suspension bridges.

The report is presented in three separate volumes:

- Volume I - Research Information
- Volume II - Preliminary Designs and Engineering Data
- Volume III - Supporting Data

Each volume is responsive to different information requirements and is essentially complete within itself. For example, those concerned with study methodology and concept development will be interested in Volume I, while practicing engineers responsible for implementation will find information in Volume II more applicable. Individuals in both categories who wish to pursue their interests in more detail will find the supporting data contained in Volume III useful.

Volume I contains the program's study methodology used in the concept development process, the development and evaluation procedures for concept designs, and a summary of concepts selected for the analyses leading to preliminary designs presented in Volume II.

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ACKNOWLEDGMENTS

The assistance and information provided by many persons in state highway departments and the Bureau of Public Roads are gratefully acknowledged. Direct contributions in the concept selection and review process by Mr. F. J. Tamanini and Mr. Lloyd Cayes of the Bureau of Public Roads, Office of Research and Development are acknowledged. Suggestions and information provided by Messrs. Odis H. Clark, Jr., Leroy A. Surtees, Jr., and Malcolm L. Steinberg of the Texas Highway Department are also acknowledged. Direct assistances provided by Institute staff members are also noted as follows: Dr. Thein Wah, who formulated the theoretical methods, Mr. Raymond E. Kirksey, who supervised computer programming and computer operation activities, and Messrs. Leonard U. Rastrelli, Robert Sherman, Norman I. Turner, and R. Kirk Gregory, who contributed concepts and ideas.

ABSTRACT

Volume I of this report summarizes research activities conducted in response to requirements for developing new, cable supported structures design concepts that will permit removal of massive support structures from the area adjacent to the roadway. Development efforts resulted in identification of bridge concepts and sign and lighting system concepts that are responsive to new, safety related design criteria. Initially, sixteen bridge concepts were examined with respect to their potentials in responding to the new criteria; eight of the sixteen design schemes were selected for subsequent preliminary analysis and concept designs. Similarly, four sign support structure concepts and four lighting system support structure concepts were selected for preliminary analysis and concept designs.

Methods of structural analysis developed for these concepts, quantitative analyses of these concepts (with respect to projected geometric, load and aesthetic requirements) and the definitive concept designs are summarized in this volume of the report. Bridge concepts selected for detailed analysis and preliminary design are identified and discussed. These are: (1) the Leaning Arches Bridge (new and modified bridge concepts), (2) the Bridle Bridge (new bridge concept), and (3) the Frame Bridge (modified bridge concept). New sign and lighting system support structures concepts selected for preliminary design are also identified and discussed.

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I. INTRODUCTION

The Structural Systems in Support of Highway Safety (4S) program sponsored by the Bureau of Public Roads is a short-range, quick-payoff research endeavor designed to reduce the severity of single vehicle accidents on the Nation's highways. The objectives of this accelerated program may be summarized as: (1) to develop structural systems concepts for the elimination of rigid obstacles and other obstructions along the highways and (2) to develop devices and structural arrangements for vehicle impact attenuation, deflection, or entrapment to assure that collisions with these devices will be of minimum severity. An examination of the statistics on single vehicle collisions confirmed the advisability of researching both approaches to the problems.

Research and findings contained in this three-volume research report concern the former approach to the solution of the problem, i.e., examination of supporting systems of highway appurtenances with the objective of effecting their elimination or relocation to points away from proximity to the edges of the roadway. Such supporting systems include bridge median piers and abutments, as well as overhead sign and lighting system support structures. The scope of work required that imaginative and creative concepts for these highway structures were to be developed; however, it was specified that these concepts be limited to those employing structural cable systems in applications which differed from those used in conventional suspension bridges.

The contents of this volume are concerned with the portion of the investigation which led to the selection and preliminary design of several feasible structural support systems which are responsive to current and projected safety standards. Included in Volume I are summaries of concepts and classifications, as well as discussions of future safety related design requirements. Concept designs developed to facilitate the evaluation process are presented for two principal rigid obstacle categories: bridge support structures, and highway sign and lighting system support structures. Finally, structures selected for preliminary design and engineering feasibility studies are identified and briefly discussed to make this volume complete as a summary of research activities. Detailed discussions and presentations of preliminary designs for new and modified existing bridges, and signs and lighting systems are contained in Volume II (Preliminary Designs and Engineering Data); supporting information for Volumes I and II is contained in Volume III.

II. STUDY METHODOLOGY

Specific project objectives concerned development of structural support systems concepts for highway appurtenances which will permit elimination or relocation of rigid obstacles and other obstructions from proximity to edges of the roadway. One aspect of the general approach to the problem involved examinations of present-day structural supporting systems of highway appurtenances with respect to current trends in highway safety requirements. In this regard, consideration was given to the February 1967 report of the special AASHO Traffic Safety Committee(1)* which suggests the adoption of two-span bridges for overpasses crossing divided highways as a means of eliminating bridge piers normally placed adjacent to highway shoulders. It was also recognized, however, that placement of a pier in the highway median has certain disadvantages. A divided highway with a median width such that a median barrier is not required by current warranting standards(2) will be made more hazardous by the introduction of a median pier and guardrail in the otherwise unobstructed median. Furthermore, the current Bureau of Public Roads instructions for new federal aid construction, which specify that a 30-foot minimum distance be provided for roadside appurtenances, have considerable merit based on single vehicle accident studies. These observations suggest that emphasis must be placed on providing the "errant" motorist with wide, unobstructed areas beyond the edges of the roadway in which to recover control of his vehicle. Thus, it was determined that rigid application of the recommendations of the AASHO Traffic Safety Committee publication(1) and the Bureau of Public Roads' Safety Publications should not be adopted as the only basis for establishing safety criteria as related to highway clearance geometry.

In this study, a roadway cross section which provides an unobstructed area between points 30 feet beyond the outside edges of the divided roadway has been chosen as a basic, safety-related geometric requirement. Structures which afford this clearance will eliminate the need for shoulder guardrail and median barriers in accordance with recently established warranting criteria(2). This geometric criterion is not suggested for rigid application, but was developed as a basis from which to begin research efforts in response to objectives of the program.

Research plans were developed to consider concepts for the removal of massive support structures grouped into two major categories: (1) bridge support structures, and (2) sign and lighting system support structures. Outlines and discussions of study methodologies employed in each of these areas are contained in the following paragraphs.

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*Superscript numbers in parentheses refer to List of References, Section V.

A. Bridge Support Structures

An initial step in the development of cable-supported bridge concepts responsive to the above safety-related geometric clearance criterion was based on the preparation of imaginative sketches and the conduct of critical conference-type critiques. A thorough search of the literature on bridges (as well as other technologies employing major structures) was made to serve as a source of inspiration and to insure that no previously conceived but unapplied idea was overlooked. These creative and review studies were conducted with an objective of identifying concepts which would be applicable to new bridge designs, as well as designs which could be used for the modification of existing bridges, to eliminate massive support structures.

Bridge concepts, identified and placed into schematic drawing form, were examined in conference by a team of project investigators, including representatives of the aerospace and marine structures disciplines. Duplications, or near duplications, were eliminated, and the remaining concepts were examined individually for feasibility, originality, and flexibility of application to both new and existing structures. Sixteen bridge concepts which appeared responsive to project requirements emerged from this review and organization process. Cables played a major role as principal load-carrying members in most of these concepts.

These sixteen bridge concepts were then reviewed and evaluated in a joint conference which included Bureau of Public Roads project technical monitors and Institute principal investigators. During this conference, eight of the sixteen concepts were selected for additional, application-potential considerations. Selections of these eight concepts were based on such considerations as uniqueness of configuration, potential applicability to modification of existing bridges, and compatibility with conventional design and construction methods.

Evaluations of these eight bridge concepts required the development of methods of analysis to demonstrate design and analvtical feasibility, and to gain an appreciati n of the structural systems' complexity. As a part of the evaluation process concept designs were developed for specific geometric and load criteria common to each of the eight bridge concepts. Such concept designs were developed to the extent necessary to achieve a first-order appraisal of system effectiveness for the basic eight structural schemes selected. One of the indicators used as a measure of system effectiveness was gross bridge weight; this parameter was judged to be a significant quantitative measure for judging the comparative effectiveness of the selected, cable-supported structures. Qualitative factors were also used in the evaluation procedure. Among these were such considerations as concept structural and construction complexity, as well as aesthetics. The use of system complexity as a comparative analysis criterion in evaluating bridge designs reflected the ultimate objective to develop bridge configurations that will be acceptable to the highway bridge technical and policy-making community. From both design and construction standpoints, engineers would be more inclined to favor the simpler system configurations if presented with a choice of several concepts.

A second conference with project technical monitors and principal investigators concerned reviews of concept designs developed for the eight structural schemes. Three basic structural schemes were selected, from eight concepts carried through the concept design stage, for additional engineering feasibility analysis. One of the schemes was judged applicable to new bridge construction only; another concept was judged applicable to modified existing bridge construction only, while the third scheme was judged applicable to both new and modified existing bridge construction. Thus, four preliminary bridge designs are identified in this volume and presented in detail in the engineering feasibility portion of the report (Volume II).

Technical efforts beyond the point of selecting the three most promising and feasible structural schemes were directed toward demonstrating design and analysis practicality and ascertaining first-order approximations of cost and implementation effectiveness. Guidelines for the technical appraisals were based on the recognition that both technical and economic details of a given design are dependent on local conditions and policies. Any attempt to be more specific than presentations of preliminary designs, especially with regard to detailed costs of construction, would be not only premature but could actually be misleading, if an attempt were made to apply the design to a localized condition.

B. Concepts for Highway Sign and Lighting System Supports

Among widely used concepts for highway sign supports are the balanced and unbalanced butterfly, cantilever, sign bridge, sign bridge cantilever, structure-mounted sign and roadside sign. Recent changes in highway practice related to safety should eliminate several of these types of signs (e.g., the butterfly designs in "gore" areas) from consideration for future use. Some other types are not relevant for the purposes of the present study (e.g., the roadside sign which has been modified to be of "breakaway" design). Attention in this effort, therefore, was focused on two main types of sign support, namely, the cantilever and the sign bridge.

Salient requirements were related to providing at least 30 feet of clearance from the edge of the pavement to the base of structural supports adjacent to the roadway(1) and providing a vertical clearance for sign support structures of 18 feet, rather than the 17 feet required for bridge structures.

As a result of a concept identification and review process similar to that accomplished for bridge concepts, four basic structural schemes emerged as deserving of further consideration in the concept-design evaluations of sign supports. Subsequent evaluations of concept designs yielded only one structural cable configuration whose application feasibility warranted the preliminary design efforts.

Constraints imposed by technical, economic, and planning factors, and considerations of emerging developments in illumination technology, allowed only a few opportunities for truly imaginative and productive concepts in the matter of lighting support structures. A concept identification and review process for lighting system support structures (similar to that accomplished for sign support structures) resulted in the identification of two basic structural schemes for concept design evaluations: cantilevered and suspension systems. Only one lighting system support structural scheme, however, was selected for preliminary design considerations.

III. BRIDGE CONCEPT DEVELOPMENT

Development of new bridge concepts to eliminate massive structures supports adjacent to the travel way began with information review processes in two areas: (1) a review of the historical trends in bridge building, and (2) technological appraisals of the state-of-the-art of bridge design as related to materials, construction techniques, and design methods. It was determined that the former study area was important from a concept identification and classification standpoint since over 2000 years of engineered bridge-building experience has been recorded. The latter study area was similarly considered important because it was recognized that modern technology, particularly in the areas of materials development and analysis techniques, will permit utilization of bridging concepts heretofore considered to be uneconomical or impractical.

A. History, Concepts, and Classifications

A literature review* was conducted to identify bridge concepts which have possible application to the objectives of this program. Bridge concepts identified through the historical review were examined with respect to recent advances in design and materials technology which could have the effect of changing a previously impractical concept into a potentially effective bridge system. The advent of high strength steels and advanced computerized analysis and design methods, in particular, seem to support the increased use of indeterminate structures such as those required for employing cable supports; structures using composite materials (including the use of glass reinforced plastics) also appeared to exhibit potentials for responding to the requirements of longer spans dictated by moving support structures away from the edge of the roadway, although their cost-effectiveness in bridge design applications has not been determined.

While, in theory, certain advantages can be realized from using new materials and analysis techniques, equally significant disadvantages become apparent when an entire bridge system is subjected to technoeconomic studies, including the aspects of current practice. For example, cable-supported structures generally are much more flexible than conventional structures of similar spans. Although this aspect, in itself, is by no means an indication of structural inadequacy, structures which exhibit a propensity toward unusual flexibility characteristics conflict with the "allowable deflection" criterion established by current codes. Furthermore, conventional static

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*A bibliography of reference material that was screened in accomplishing this review is included in Appendix A of Volume III (Supporting Data).

methods of design and analysis must be augmented (for purposes of design of these more flexible systems) by rather sophisticated dynamic analyses and experimental studies for certain of the new bridge concepts.

The historical and technological reviews led to identification of sixteen bridge concepts which exhibited the potential for effectively providing the relatively long spans necessary to effect elimination of massive support structures adjacent to the travel way. The sixteen bridge concepts are illustrated in Figures 1 through 16. In developing these concepts, no design or economics-related selection criteria were employed; hence, the concepts presented include cable-supported systems (nonconventional suspension bridges) as well as rigid frames, arches, and trusses. Several of the concepts possess the dual capability of possible use to effect removal of massive support structures (principally median piers) from existing bridges, as well as being potentially effective new bridge concepts. Where this dual design capability exists, it is suggested on the concept sketches.

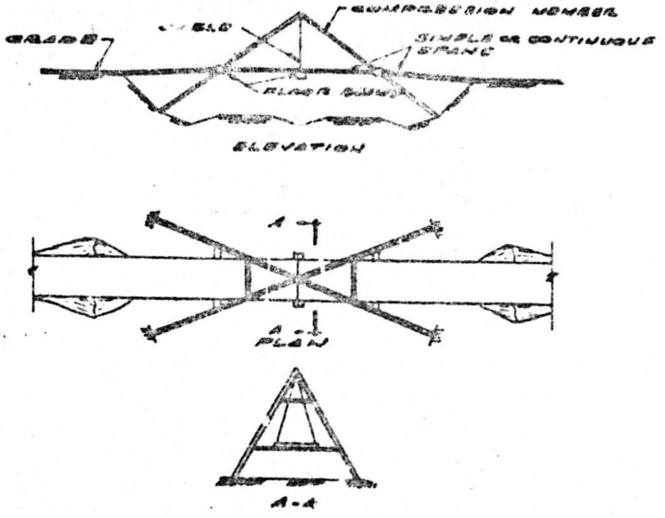
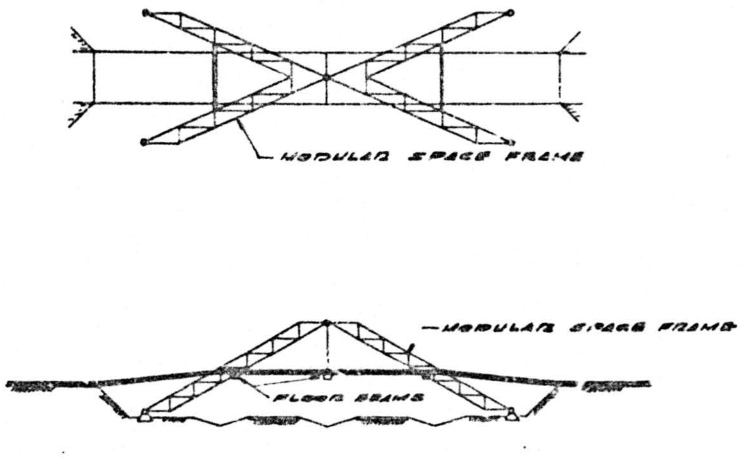


FIGURE 1. "A" FRAME BRIDGE CONCEPT



BRIDGE CONCEPT EMPLOYING SPACE FRAME SUPPORTS WITH STANDARD MODULAR CONSTRUCTION; DESIGN PERMITS ADDITION OR DELETION OF MODULES TO ACCOMMODATE GRADE DIFFERENCES AND SPAN DIFFERENCES CAUSED BY SKEWS.

FIGURE 2. MODULAR SPACE FRAME BRIDGE CONCEPT

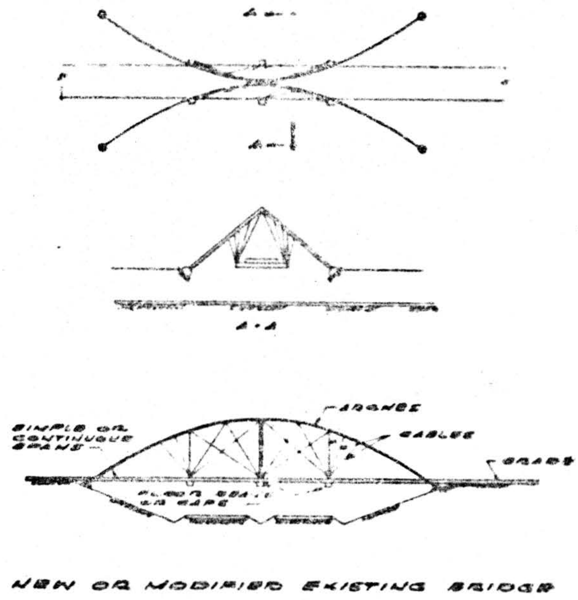


FIGURE 3. LEANING ARCHES BRIDGE CONCEPT

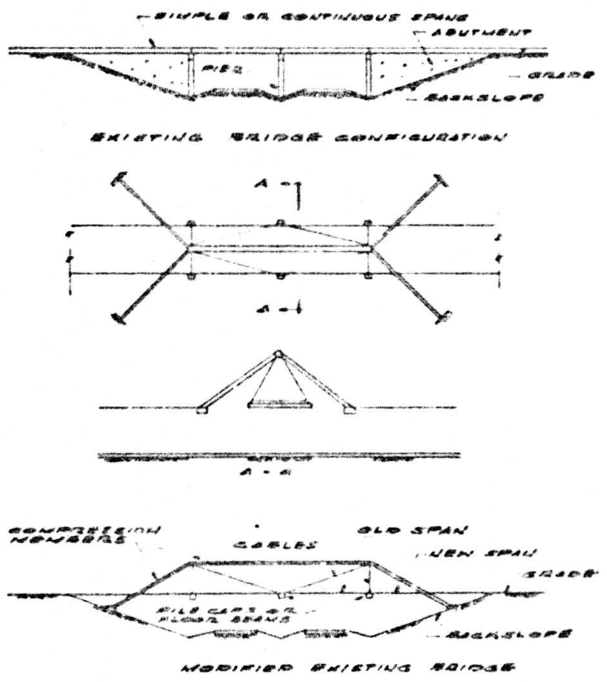
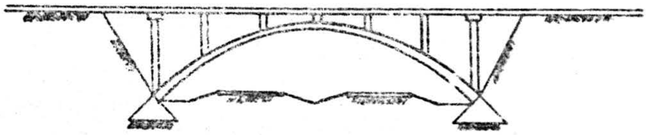
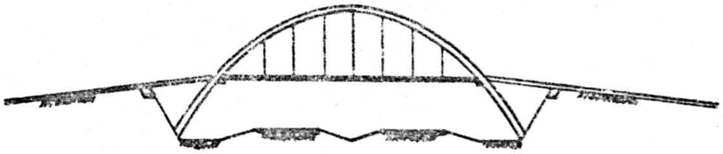


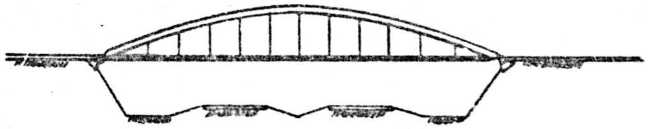
FIGURE 4. THREE-DIMENSIONAL FRAME BRIDGE CONCEPT



(1) Crossing Road Grade Above Thruway (Possible Tie Under Roadway)



(2) Crossing Road Grade Same as Thruway (Possible Tie Under Roadway)



(3) Crossing Road Grade Above Thruway (Roadway Serves as Tie)

FIGURE 5. ARCH BRIDGE CONCEPTS

(Typical of St. Michel Bridge, Toulouse)

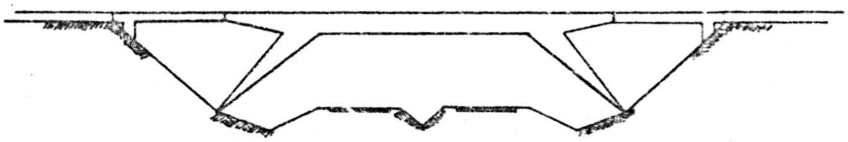
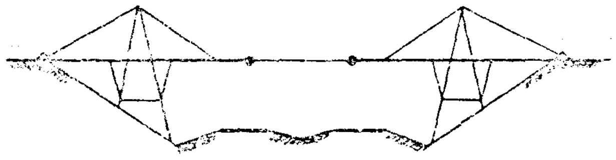


FIGURE 6. PRESTRESSED (POST TENSIONED) CONCRETE BRIDGE CONCEPT

(Suggested by the Proposed Polcevera Viaduct, Antwerp Bridge and Göteborg Bridge



(Suggested by the Norderelbe Bridge, Hamburg; Mono Cable Bracing)

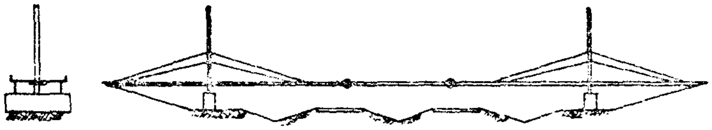
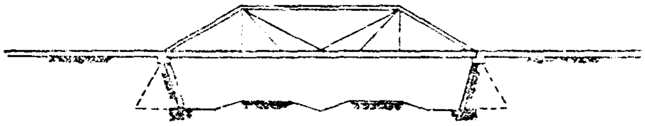


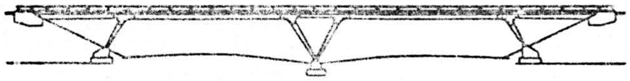
FIGURE 7. SUSPENSION/SUSPENDED SPAN BRIDGE CONCEPTS



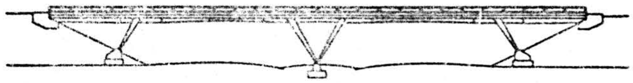
(1) CABLE TRUSS

(2) DOUBLE CANTILEVER

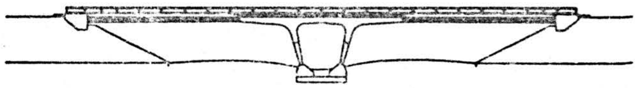
FIGURE 8. TRUSS BRIDGE CONCEPTS



RED DEER BRIDGE

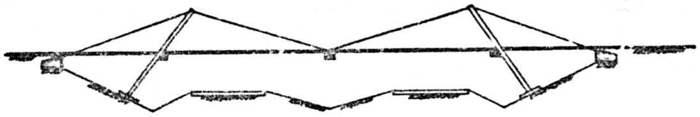


WETASKIWIN BRIDGE

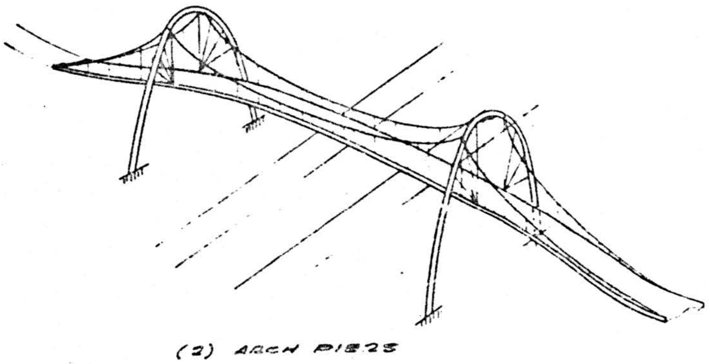


MENAIX BRIDGE

FIGURE 9. STEEL BRIDGE CONCEPTS



(1) LEANING PIERS



(2) ARCH PIERS

FIGURE 10. UNCONVENTIONAL SUSPENSION BRIDGE CONCEPTS

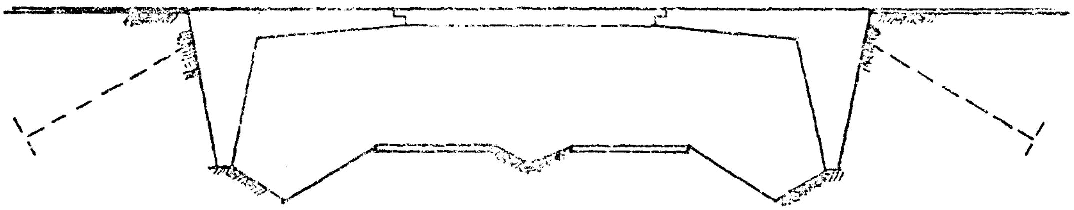
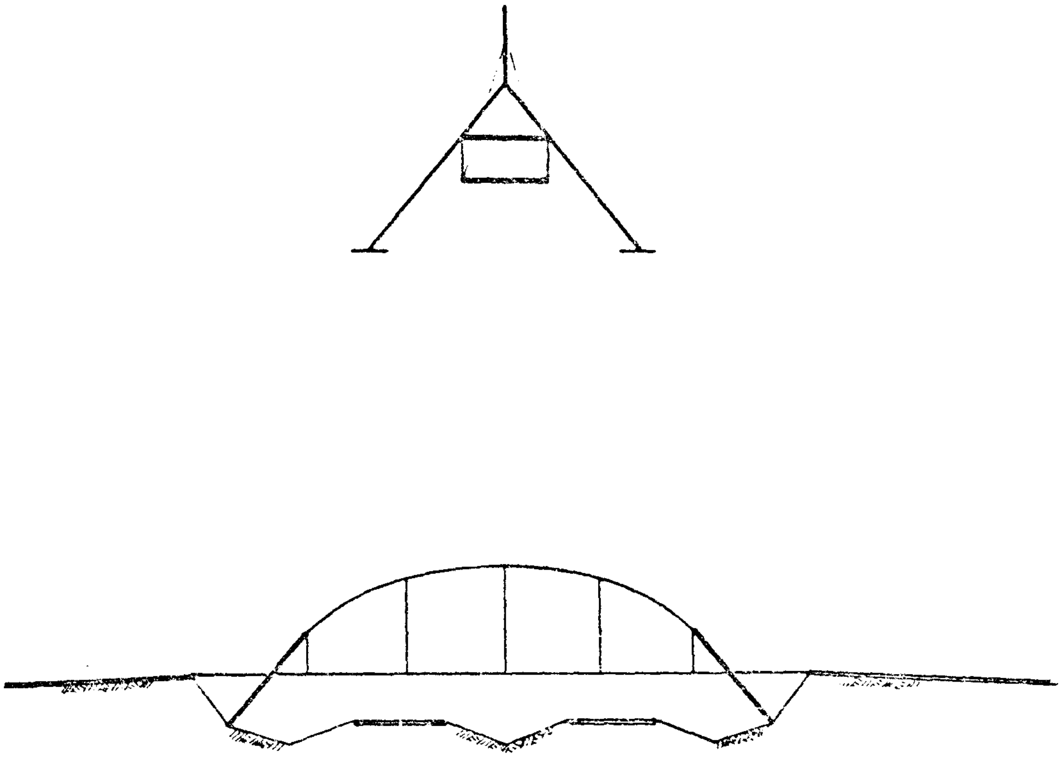


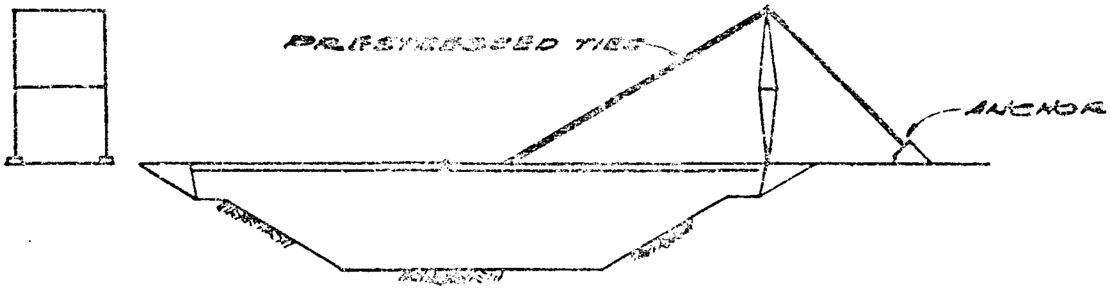
FIGURE 11. DOUBLE CANTILEVER WITH SUSPENDED SPAN BRIDGE CONCEPT



(Typical of Monorail Bridge, W. Germany)

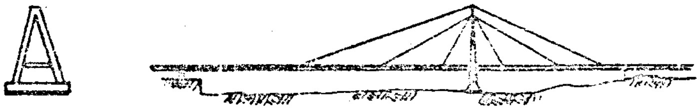
FIGURE 12. BRACED ARCH BRIDGE CONCEPT

(Bridge over River Tartaro, Canada)



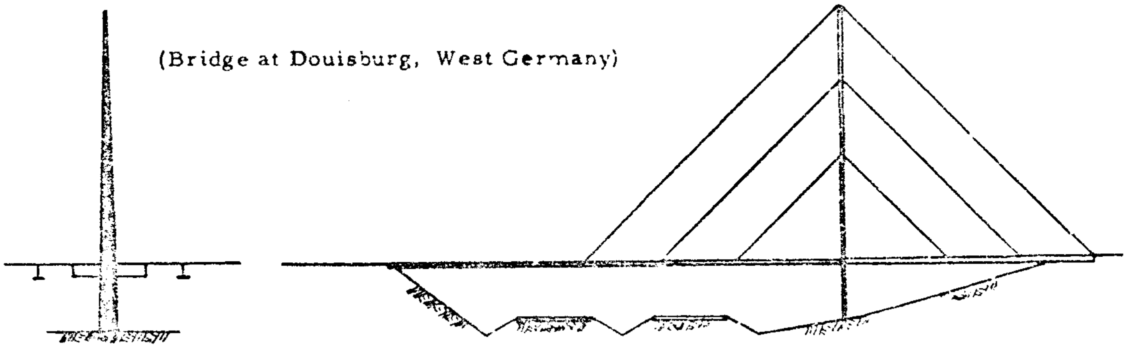
(a) Bridle Bridge

(Bridge at Severin, Cologne: An Unsymmetrical Bridle Chord Bridge)



(b) Bridle Chord Bridge

(Bridge at Douisburg, West Germany)



(c) Stayed Girder Bridge

FIGURE 13. "BALANCED ELEMENT" BRIDGE CONCEPTS

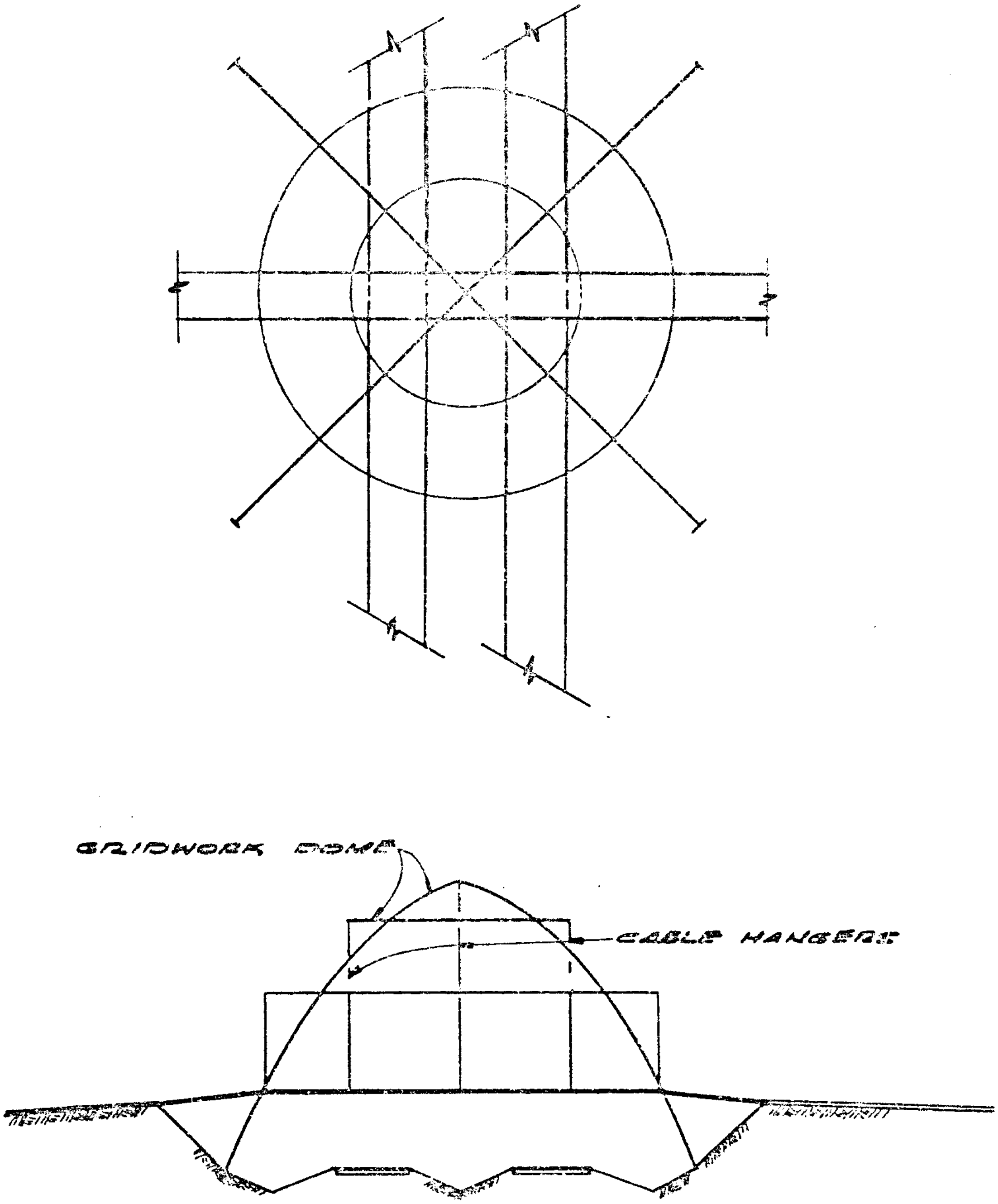


FIGURE 14. DOME BRIDGE CONCEPT

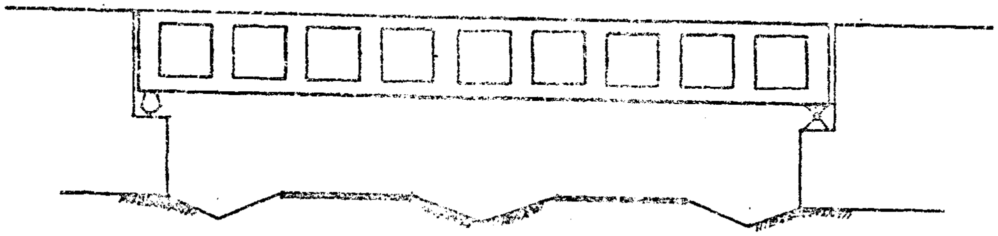


FIGURE 15. VIERENDEEL TRUSS BRIDGE CONCEPT

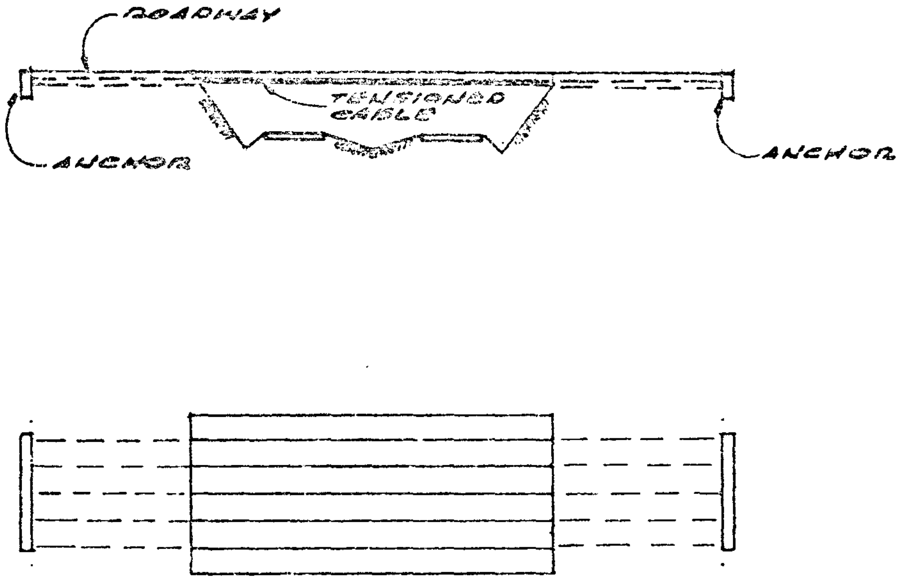


FIGURE 16. TENSIONED CABLE BRIDGE CONCEPT

B. Design Requirements for Bridges

The sixteen bridging schemes illustrated in Figures 1 through 16 reflected criteria based on general appraisals of design requirements for bridges responsive to new safety standards. It was noted that the exercise of additional selectivity to further reduce the number of concepts must be based on more specific design requirements if the final selections were to be meaningful. Hence, at this stage of the research investigation, design requirements for highway bridges that must meet current and projected safety standards were developed and employed in the evaluation and selection process. These included the following geometric, load, and aesthetic requirements established to assist in the selection process, as well as to guide subsequent concept design efforts.

1. Geometric Requirements

Current practice was considered to be vested in the Special AASHO Traffic Safety Committee Report entitled, "Highway Design and Operational Practices Related to Highway Safety and AASHO Specification."(1) As noted in Section II, however, it was deemed necessary to take the geometric design standards for bridges one step further. Projected design requirements, if they are to be effective in eliminating obstructions for the errant motorist, must include provisions that there be no obstruction within the median, that a median width of 60 feet be maintained beneath crossing structures (to assure that no median barrier is warranted), and that 17 feet of vertical clearance be maintained to a point 30 feet from the outside edges of the two roadways.

Geometric design requirements related to horizontal and vertical clearances (illustrated in Figure 17) are considered to be practical future minimums if effective improvements in safety are to be realized by moving or eliminating supporting structures from the areas adjacent to the travel way. For purposes of standardization of conditions for the development of concept designs for the structural schemes selected, the crossing structure was considered to intersect at 90° (0° skew angle) and carry a two-lane, 24-foot roadway. A standard dimension of 30 feet (center-to-center of floor beam supports) was employed for the width of the crossing structure in developing concept designs.

2. Design Load Requirements

Loads on future bridges will likely be similar in magnitude to those that are currently imposed. However, in specifying the load spectra to be used in bridge design, it may be necessary to include dynamics.

Current AASHO loading standards may not be adequate for use in designing cable-supported bridges which are responsive to the geometric

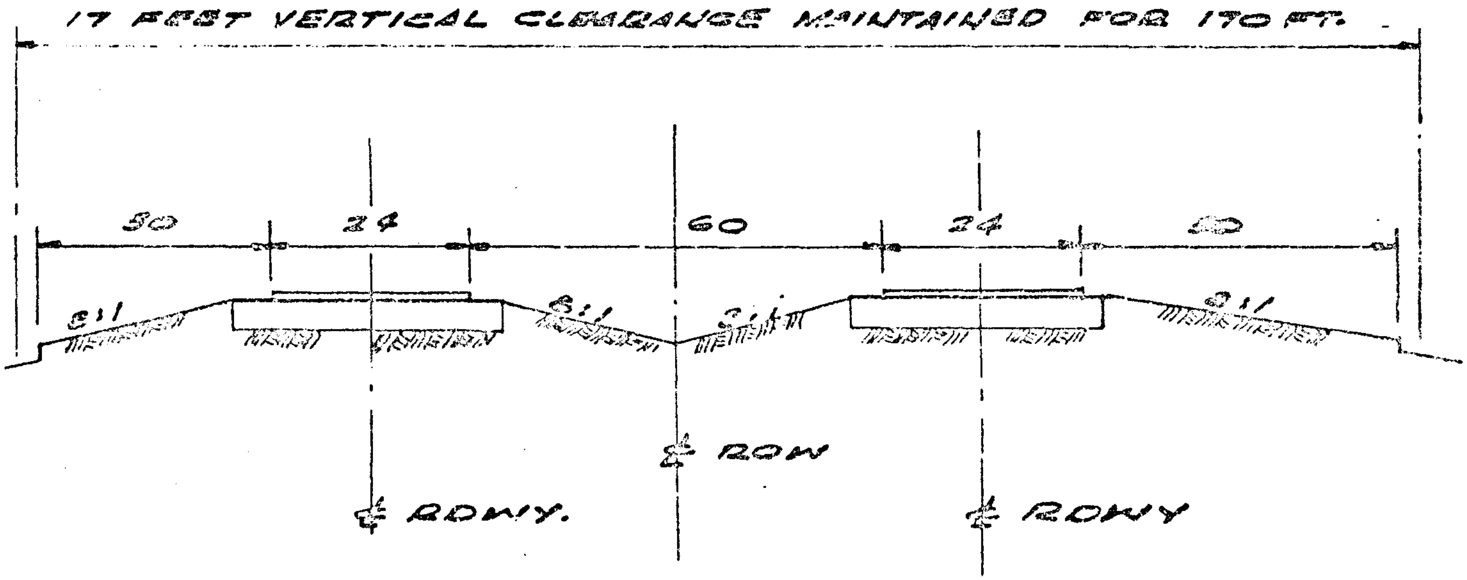


FIGURE 17. GEOMETRIC REQUIREMENTS FOR CROSSING STRUCTURE ESTABLISHED BY SAFETY CONSIDERATIONS

requirements described previously. This situation may be brought about by longer spans and more flexible structures evolving from design requirements which suggest the use of cable-supported structures. Although it may ultimately be necessary to include some form of a bridge dynamic analysis in future bridge design specifications, the present investigations made use of representative, current load specification in order to compare bridge concepts from a design-effectiveness standpoint.

Accordingly, a H20-S16 loading was employed in developing concept designs for comparison purposes. Specifically, 640 pounds per lineal foot per lane plus an 18-Kip concentrated load per lane, placed for maximum moment, was employed as a basic load. Impact was computed by employing the AASHO formula for impact as a means of arriving at a dynamic load factor. For the preliminary analysis and concept design purposes, longitudinal forces and wind loads, thermal loads, uplifts, etc., were not considered; dead loads were estimated as uniform lane loads.

3. Aesthetics

Preservation of the beauty of the highway system through attention to structural design aesthetics has become an increasingly demanding design requirement in recent years. At this point in the development of design requirements for long span bridges that are responsive to program objectives, it may only be said that the design must be "beautiful in art and manifesting of taste." Although it would be difficult to eliminate potentially effective bridge concepts based on aesthetic considerations alone, certain types of trusses and heavy plate girders would not be favorably considered in this regard.

C. Bridge Systems Analyses and Concept Designs

The sixteen bridge concepts (Figures 1 through 16) were examined in conference by project technical monitors and principal investigators. This review employed the design criteria outlined in Paragraph B as a guide and resulted in the identification of eight cable-supported bridge concepts which warranted preliminary systems analysis and applications consideration. These eight concepts are identified in Table I; line drawings of the structural schemes including geometrical descriptions which meet the horizontal and vertical clearance requirements specified in Figure 17 are presented in conjunction with analysis and design discussions of the eight structural schemes in the following paragraphs.

1. Structural Analyses

Methods of analysis were developed for the eight bridge concepts identified in Table I. These analyses, presented in Appendix B of Volume III, are based on specific definitions of bridge structural configurations.

TABLE I. CABLE-SUPPORTED BRIDGE CONCEPTS SELECTED FOR CONCEPT DESIGN CONSIDERATION

Concept Number	Figure Number	Title	Description
1	18	"A" Frame	Three-dimensional frame employing cables to support floor beams at ends of simple spans: may be employed in new or modified existing bridges.
2	19	Leaning Piers	Simple span support in two vertical planes on either side of roadway; supporting structure leans inward to minimize hazard at abutment.
3	20	Braced Arch	Single arch centered over roadway centerline with "A" frame supports on either end; continuous cable-supported girders carrying roadway.
4	21	Bridle Bridge	Support from one side supporting a cantilever and a simple span.
5	22	Stayed Girder	Single supporting tower with cable supports holding a single continuous girder.
6	23	Frame Bridge	Rigid frame with cables supporting simple spans.
7	24	Leaning Arches	Double arches leaning inward; cable-supported roadway.
8	25	Dome Bridge	Circular arch systems forming a dome to support roadway system via cables.

Preliminary to embarking on development of analyses, it was necessary to specify certain aspects of the structural system (e.g., continuous spans or simple spans, pinned connections or fixed connections, etc.). In specifying these design conditions, attempts were made to incorporate features which would enhance the applicability of the concepts to the design objective. For example, new bridge concepts which may also be employed to support the floor and beam systems of an existing bridge to allow removal of a median pier were defined in a manner responsive to both uses. As these definitions of design schemes were made, it became apparent that in some instances alternate schemes (e.g., continuous spans rather than simple spans) possessed certain advantages with regard to ultimate design efficiency. A detailed sensitivity analysis of the design parameters could have been conducted to effectively establish optimum designs. However, such studies were considered to be premature for the preliminary analyses and concept designs being considered; therefore, one representative structural configuration (which appeared most responsive to program objectives) was selected for each concept. Parametric studies to determine the most effective designs were deferred for consideration in subsequent, more detailed portions of the investigation.

2. Development of Design Forces, Moments and Shears, and Concept Designs

Methods of analysis (presented in Appendix B of Volume III) were used with geometric and load conditions discussed in Paragraph B (of Section III) and specific structural schemes to develop design forces, moments, and shears (as appropriate), for components of each of the eight bridge concepts (see Table I). Developments for use in subsequent concept design considerations involved the construction of influence diagrams for principal structural members and floor system members, and included the use of these influence diagrams in a conventional manner to acquire design forces, moments, and shears. The analysis details differ slightly between the determinate structures (Concepts 1, 2, 4, and 6) and the indeterminate structures (Concepts 3, 5, 7, and 8); these differences are noted in the analysis summaries which follow. Influence diagrams used in developing concept designs are included in Volume II for designs selected for feasibility studies and in Appendix C of Volume III for concepts not selected for study beyond the "concept" design stage.

It is important to note that the analyses and evaluations of the eight bridge concepts summarized in the following paragraphs are based on load and geometric requirements that are consistent between concepts. As previously noted, the geometric requirements for crossing structures were specified for a zero-degree skew-angle crossing structure as shown in Figure 17. Loading requirements applied to each bridge consisted basically of an H20-S16 loading; however, several of the code-specified refinements in load placement and magnitude were simplified or deleted so as not to unnecessarily complicate the preliminary analysis and concept design procedure. Discussions of the procedures employed in analyzing the structures and comments on the concept designs for the eight structural schemes follow.

- "A" Frame Bridge

This bridge concept, illustrated in Figure 18, was conceived principally as a method for permitting the removal of a median pier while retaining an existing floor system. The main structure (consisting of four main members which form a pyramid) supports three floor beams which form the supports for four simple spans. The center floor beam is cable-supported from the apex, while the two outer floor beams are pin-connected to the main members. It is important to note that the roadway girders and floor beams do not provide tension ties between legs.

The analysis of this bridge concept considered the structure as being a statically determinate space frame that is axisymmetric about a vertical axis through the apex (see Appendix B of Volume III).

A significant observation resulting from the analysis concerns the large bending moment in the relatively long main members while a load is on the two spans immediately adjacent to the floor beam/main member connection point. Concept design of the main members, treated as beam-columns, resulted in relatively heavy, 157-foot-long box girders. The cable supports attached to the center floor beam contribute very little weight to the principal structural system. Design of the floor system was dictated by the geometry of the main frame; simple spans of 34, 85, 85, and 34 feet were required. The stringer system within the 85-foot spans consist of 30WF130 beams which contribute significantly to the weight of the bridge. An alternate plate or continuous girder design could conceivably reduce the dead weight; however, the interspan relationship dictated by main frame geometry would not permit a high degree of design optimization.

On the basis of total weight, the A-Frame Bridge does not compare favorably with other concepts responsive to identical load and geometric requirements. Additionally, the design is not particularly efficient (primarily as a result of bending in relatively long frame members) nor is it as aesthetically pleasing as other bridge concepts.

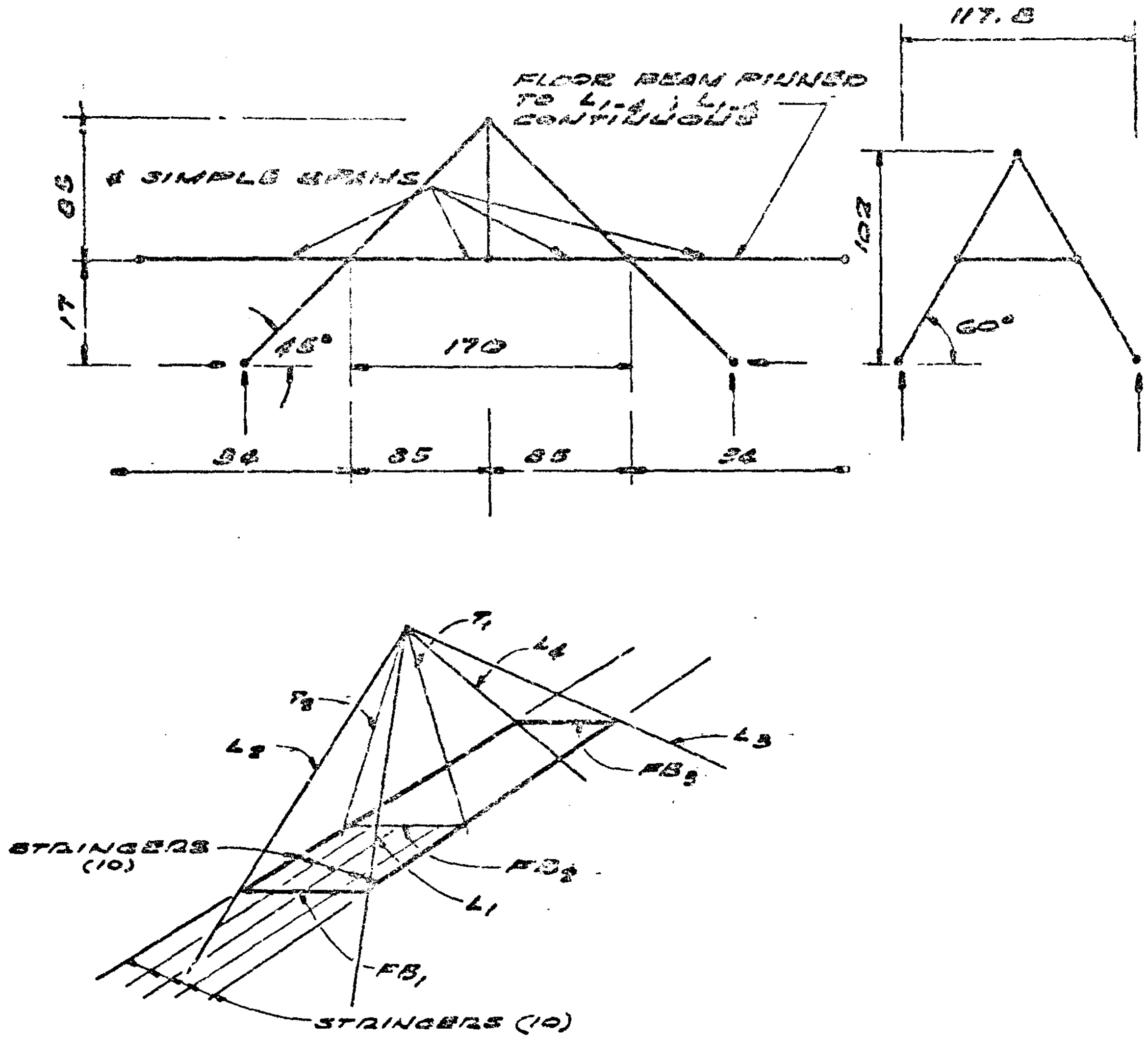


FIGURE 18. BRIDGE CONCEPT NO. 1: "A" FRAME

- Leaning Piers Bridge

An attempt to acquire additional horizontal clearance by leaning the supporting piers inward is reflected in the concept illustrated in Figure 19. Note that only two simple spans are employed and that there are no connections between the main girders and the leaning piers.

This structure is statically determinate and may be analyzed by considering the verticals, girders, and cables found in one of the two vertical planes of the main structure. Analysis methodology for this structure is presented in Appendix B of Volume III. Computations of design forces, moments, and shears for the main structure and the floor system members reveal that the relatively long span girders (which form the two 119-foot simple spans) must resist relatively large bending moments as well as a substantial axial force.

Analysis considerations reflect the situation that the main structural members are subjected only to tensile or compressive loads; the horizontal girders, however, must be designed as beam columns. As pin-connected, compression members, the leaning piers are relatively efficient. A doubly symmetric box section was selected to fulfill concept-design requirements for the leaning pier members. The horizontal girders must be considered as part of the principal structure since they are required to carry a significant compressive force. Concept design for these beam columns resulted in 119-foot-long, 61-inch-deep plate girders. Floor system requirements were satisfied by spacing floor beams (which span between horizontal plate girders) on 23.8-foot centers; four stringers span between floor beams in each of eight spans. Standard rolled shapes were selected to fulfill design requirements for the floor system.

In combination, the large compressive forces and bending moments imposed on the horizontal girders do not suggest an effective design. While this particular design has certain advantages directly related to acquiring required horizontal clearances, the preliminary analysis indicates that a severe weight penalty may be necessary in gaining these advantages. Consideration may be given to using smaller acute angles between the cable ties and the girders, as well as to employing piers approaching more nearly vertical, in an attempt to minimize the adverse beam-column effect within the main girders.

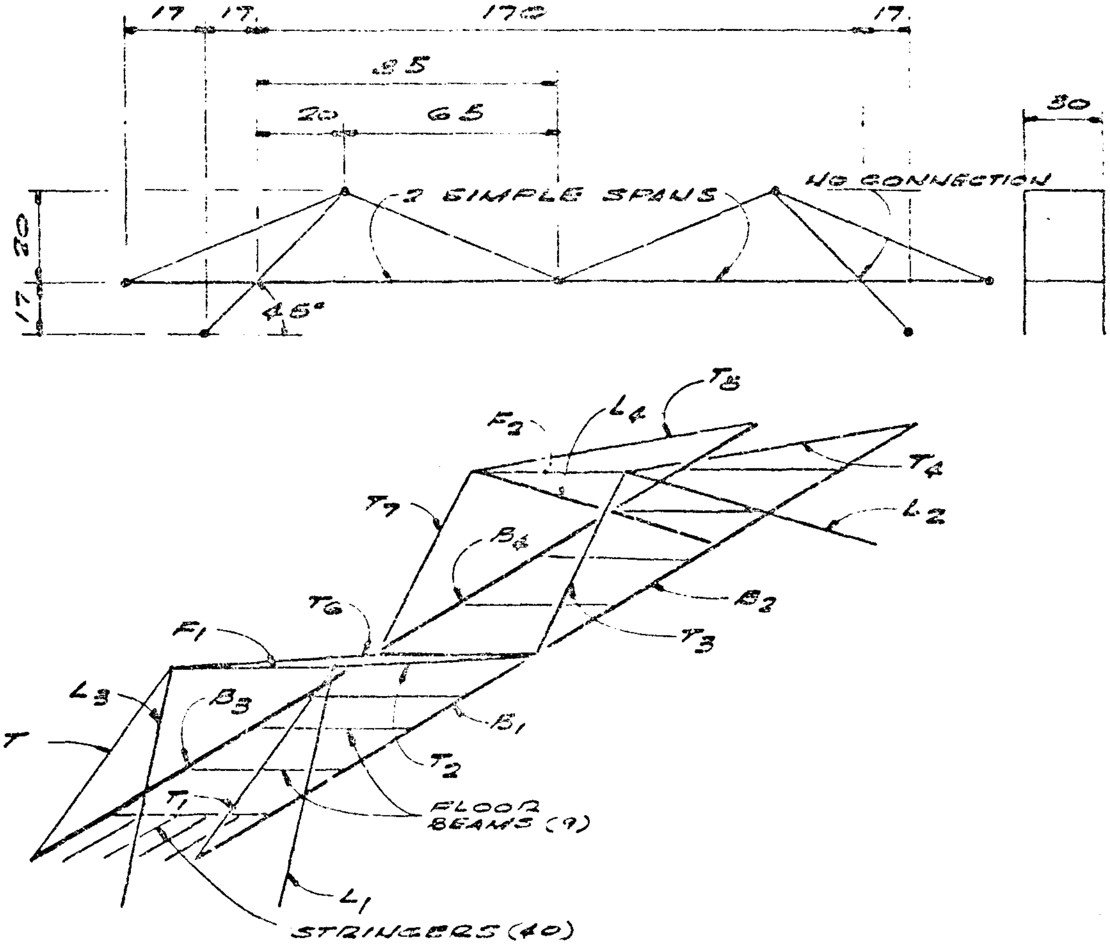


FIGURE 19. BRIDGE CONCEPT NO. 2 LEANING PIERS

Braced Arch Bridge

This concept, illustrated in Figure 20, was based on a monorail bridge design used in West Germany. A single parabolic arch springs from two "A" frames at either end of the bridge; the frames permit passage of the roadway directly beneath the arch. The arch and frame are integral at the spring point; furthermore, the roadway ties to the end frames. The roadway is suspended from the arch by cables which connect to the ends of floor beams that frame between the two continuous girders.

This structure is statically indeterminate and, for final design purposes, must be analyzed by considering the flexibility of the arch and the cable ties since they provide elastic supports for the continuous girders. (An analysis method is summarized in Appendix B of Volume III). For preliminary analysis and concept design purposes, however, the arch and the continuous girders were analyzed separately. In the arch analysis, concentrated loads were considered as entering the arch through inextensible hangers; uniform live loads and dead loads were considered to act as uniform loads directly on the arch. The continuous girders were treated as constant-stiffness beams on nonyielding supports. Influence diagrams for the girders, and reactions at supports used for determining cable forces, were obtained by employing the Mueller-Breslau principle.

Design computations assumed that dead loads and live loads are applied uniformly to the arch. This assumption proved to be adequate for concept design purposes since it became apparent that the arch is ineffectively employed by using the cable hangers in the manner illustrated in the design sketch. In addition, considerations related to system stability to side loads (including the out-of-arch plane loading configuration) and the end-frame detail reveal that the design scheme is not particularly effective in responding to highway-related load and geometric requirements. However, several design optimization alternatives could be pursued. For example, arrangement of the cable support system might be altered to permit uniform distribution of loads to the arch. Additional consideration could also be given to making the end "A" frames more effective by employing a space frame arrangement or a portal frame.

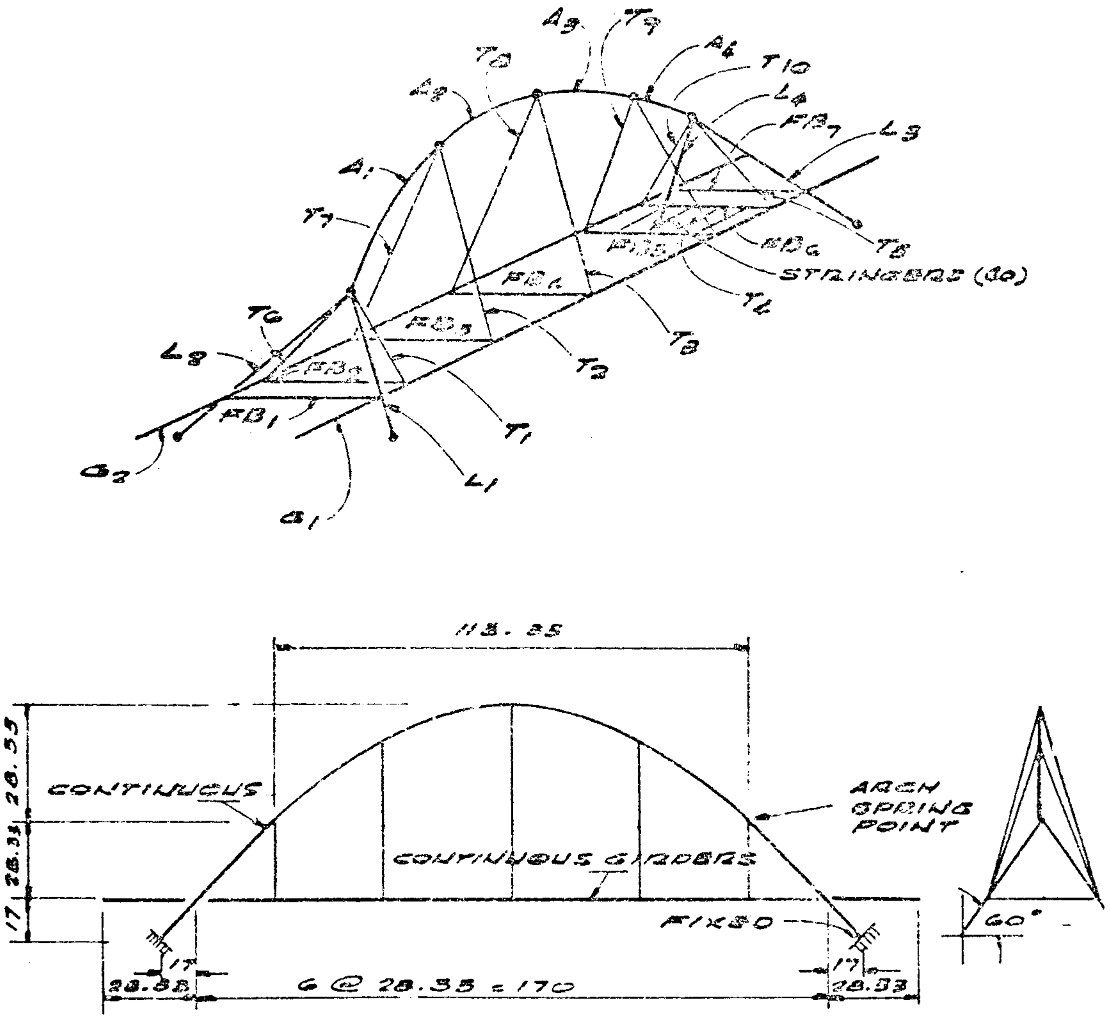


FIGURE 20. BRIDGE CONCEPT NO. 3: BRACED ARCH

Bridle Bridge

As illustrated in Figure 21, this concept is an unsymmetrical "balanced element" bridge, patterned after a bridge over the River Tartaro in Canada. A cantilever span, supported by a cable tie, supports one end of a simple span. A compression member, considered pinned at both ends, supports the cantilever span tie and the anchor tie.

This structure is statically determinate and may be analyzed by considering forces acting in a plane containing a vertical member, cable ties, and horizontal girders (the analysis method in Appendix B of Vollume III). Although the preliminary analysis indicates a relatively effective distribution of design loads, the cantilever girder is called upon to resist relatively large bending moments (positive and negative) in combination with compressive forces. Design optimization may be achieved by moving the cantilever support point, thereby effecting a more even distribution between positive and negative bending moments.

As a concept, this bridge seems to possess design advantages in effectively responding to the horizontal clearance demands outlined in Figure 17. The beam-column design requirement (noted in discussion of the Leaning Piers Bridge) is also present in the cantilever girder. However, the supporting cable can be located in a manner which achieves a balance between positive moments (in the portion of the beam adjacent to the vertical supporting column) and negative moments over the support point, thereby providing a potential for minimizing adverse beam-column effects. The concept is responsive to program requirements in terms of bridge weight and aesthetics. Since the simple span carries no compressive load, it may be sized by conventional design methods. Vertical members are considered pinned at both ends, thereby permitting design as a square box column. The cable supports are tension ties constructed from high-strength cables or rods. The floor system (consisting of floor beams and stringers on 25-foot spans) seems to be effective from a weight standpoint, and design optimization would probably yield additional weight savings.

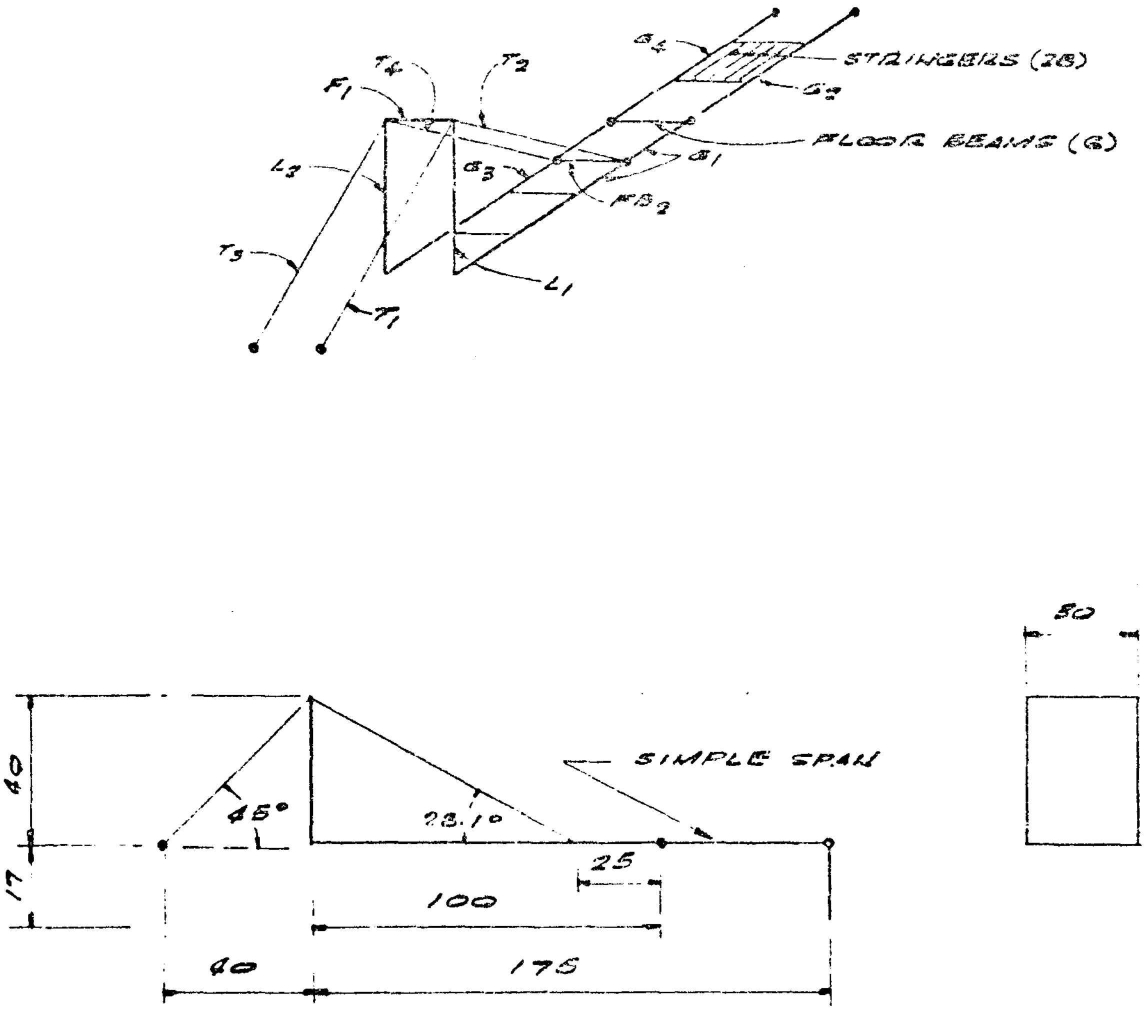


FIGURE 21. BRIDGE CONCEPT NO. 4: BRIDLE BRIDGE

- Stayed Girder Bridge

Reflecting a bridge at Douisburg, West Germany, the Stayed Girder Bridge (see Figure 22) uses a single continuous girder supported by six cables extending from a single vertical support. Because imbalances may exist between cables on either side, the vertical support is fixed to its base. Floor beams cantilever outward from both sides of the continuous girder at seven points; a system of stringers span between the floor beams.

As a statically indeterminate structure, methods of analysis must consider the complete vertical/cable tie/continuous girder system (see Appendix B of Volume III). For a preliminary analysis, however, the continuous girder was considered as a constant stiffness beam on nonyielding supports. The Mueller-Breslau principle was used to obtain influence diagrams for moments and support reactions in the continuous structure. Support reactions were used to develop tension loads for the cable system and forces acting on the vertical column. The particular design selected includes seven spans supported by cables and the vertical column.

As a concept, this bridge is pleasing in appearance. A single supporting column and several parallel cables combine with a single box girder to form an aesthetically acceptable structure. Relatively complex analysis methods prohibited complete optimization during the concept design stage. Considerable flexibility is an inherent characteristic that may be realized in adjusting, for example, span lengths, and cable stiffensses, to obtain an optimum design.

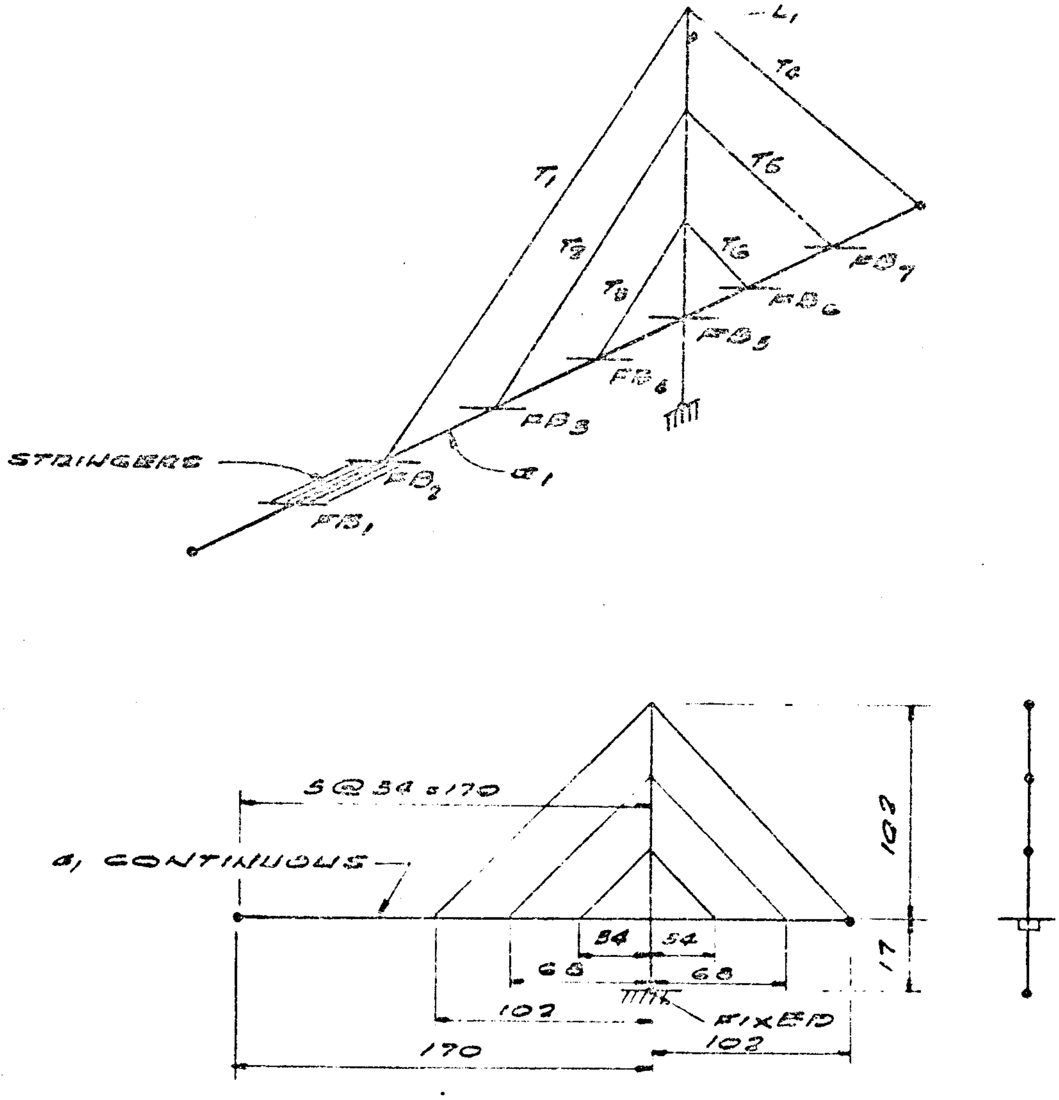


FIGURE 22. BRIDGE CONCEPT NO. 5. STAYED GIRDER

- Frame Bridge

This bridge concept (shown in Figure 23) employs a three-dimensional rigid frame which spans the roadway to be crossed and which straddles the crossing roadway. The crossing roadway is supported by a cable system which connects to floor beams; three floor beams divide the bridge into four simple spans.

The Frame Bridge is a three-dimensional, statically indeterminate structure. Conventional frame analysis methods may be employed to obtain structural response to loads applied in the vertical, center line plane (see Appendix B of Volume III). The analysis is simplified by the use of simple span stringers rather than by continuous girders. For the concept design, the frame members were configured as plate girders and were designed to carry the bending moments computed by a conventional frame analysis. Based on computed weights and aesthetics, the Frame Bridge is not as promising as the other concepts considered herein. Its advantages seem to lie in the ability to accommodate existing bridge modification requirements. Floor systems design and span relationships (when compared to the "A" Frame Bridge) are more desirable because the four spans are equal in length. The bridge concept could be considered as a modification of the "A" Frame Bridge design scheme.

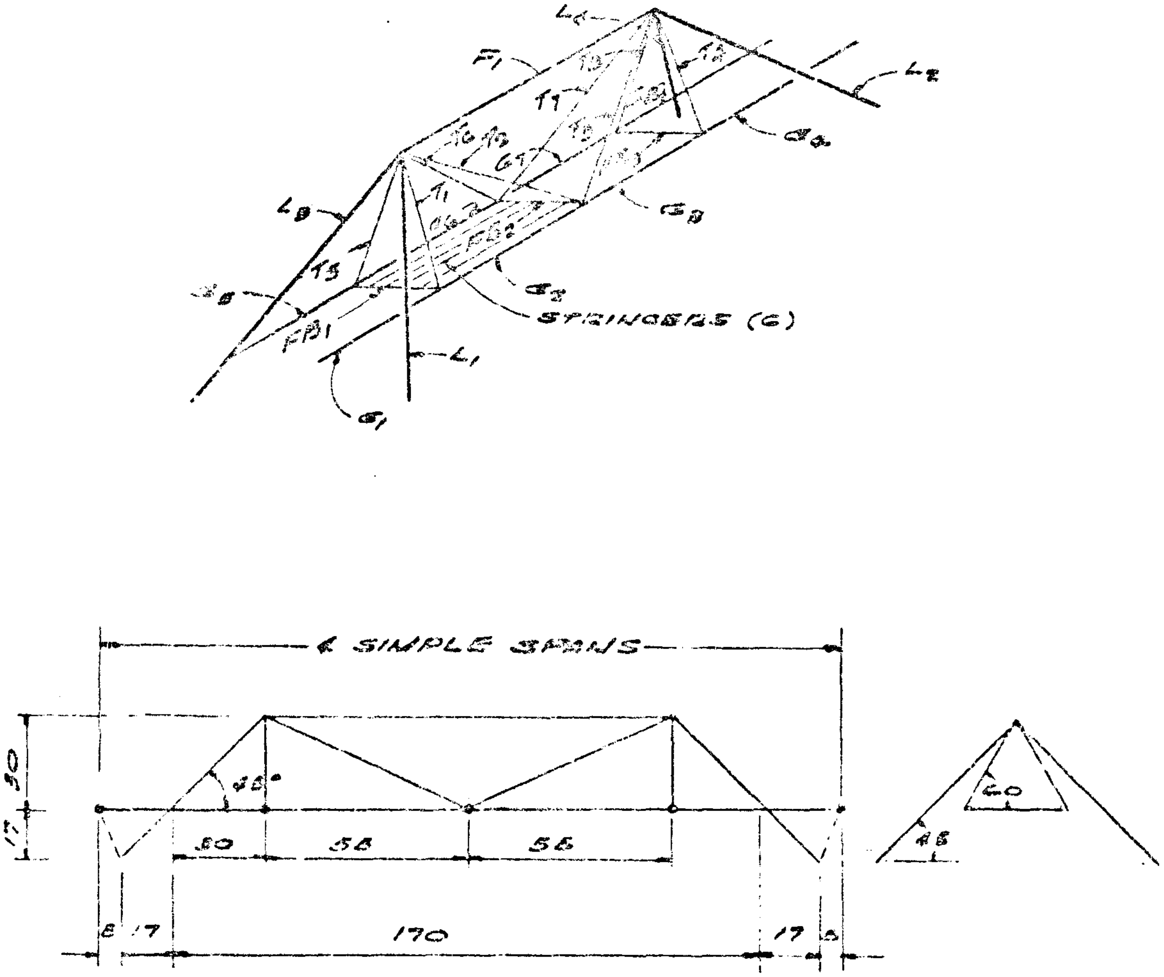


FIGURE 23. BRIDGE CONCEPT NO. 6: FRAME BRIDGE

Leaning Arches Bridge

The concept shown in Figure 24 consists of two arches which lean inward to straddle the crossing roadway. The crossing roadway, in turn, is supported by cables which connect the arches to floor beams; the supporting cables act in the planes of the arches. For a new bridge, continuous girders span between the abutments over three supporting floor beams.

As a three-dimensional, statically indeterminate structure, methods of analysis must include consideration of the interactions of the total system, including arches, flexible cable supports, and continuous girders. For concept design purposes, however, each element may be analyzed separately. Three concentrated loads were applied at the crown and quarter points of the arch to obtain maximum bending moments (crown and spring) due to concentrated loads. Uniform dead loads and live loads were considered to be evenly distributed to the arch through the fifteen cable supports. The Mueller-Breslau principle was employed to acquire influence diagrams for the moments and support reactions in the continuous plate girders. Support reactions were employed to acquire cable design forces.

An aesthetically pleasing concept, the bridge combines two efficiently loaded parabolic arches with continuous plate girders. The arches lean inward and joint at the crown in a manner permitting ease of framing for side load restraint and stability. The roadway is supported by two continuous plate girders which, in turn, are supported at three interior points by a system of cables. The cable system acts in the planes of the arches distributing concentrated floor-beam loads to the arches.

Several potential design optimization alternatives appear feasible; for example, the number of continuous girder support points could be increased. In the extreme case, a girder could be made to function as a stiffening structure as in the case of conventional suspension bridges. As a result of parametric studies, arch designs, as well as the cable system patterns, may be altered to effect optimization. In summary, the Leaning Arch concept is conducive to various optimizations, has a total system weight which appears competitive with other concepts, and is aesthetically pleasing.

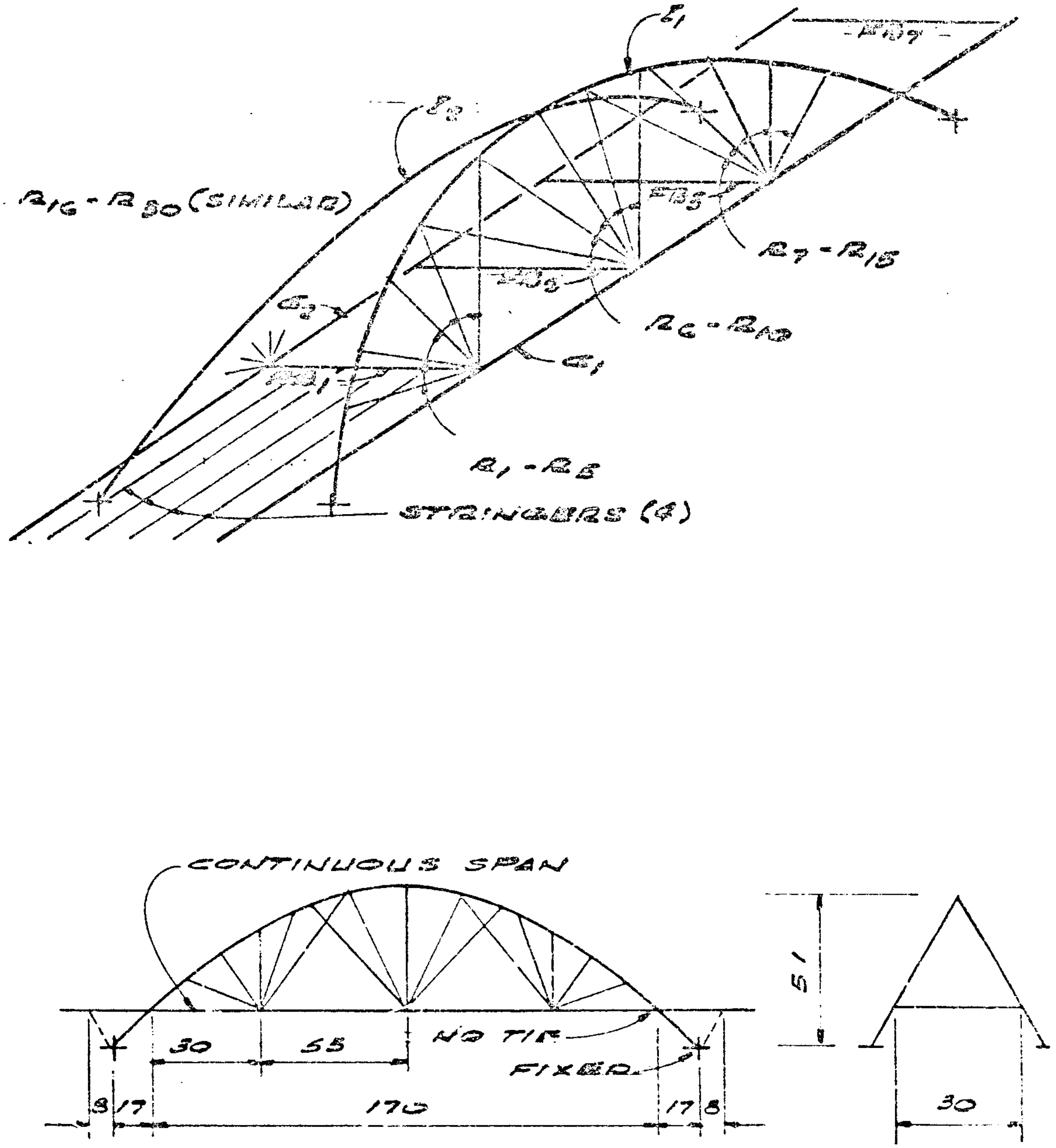


FIGURE 24. BRIDGE CONCEPT NO. 7:
LEANING ARCHES

Dome Bridge

A unique concept which employs two circular arches which intersect at right angles over the centers of the crossed and crossing roadways is illustrated in Figure 25. The crossing roadway is suspended from cables that connect to the arches at joints formed by stiffening rings; these rings intersect the arches in two horizontal planes. The floor system is a stringer and beam combination spanning four simple spans.

The Dome Bridge may be analyzed as two circular arches connected by horizontal rings. For concept design purposes, however, the arches were considered to be parabolic and subjected to hanger loads in the plane of the arches at ring intersections. The floor system consisted of four simple spans.

To accomplish the concept design, it was necessary to make certain assumptions concerning the manner in which the arch is loaded. Uniform dead loads and live loads on the floor system were assumed to load the arches in a uniform manner. As may be noted in the conceptual sketch (Fig. 25), the arches are actually loaded at discrete points where the hangers join the arches. If these loads were injected at the hanger locations (as would actually be the case), more severe moments could be realized. To further detract from design effectiveness, the arches and rings comprising the principal structural system are relatively long in span. Further, attempts to keep the loads within the planes of the arches results in two, relatively long floor beams which contribute significantly to the weight of the total system.

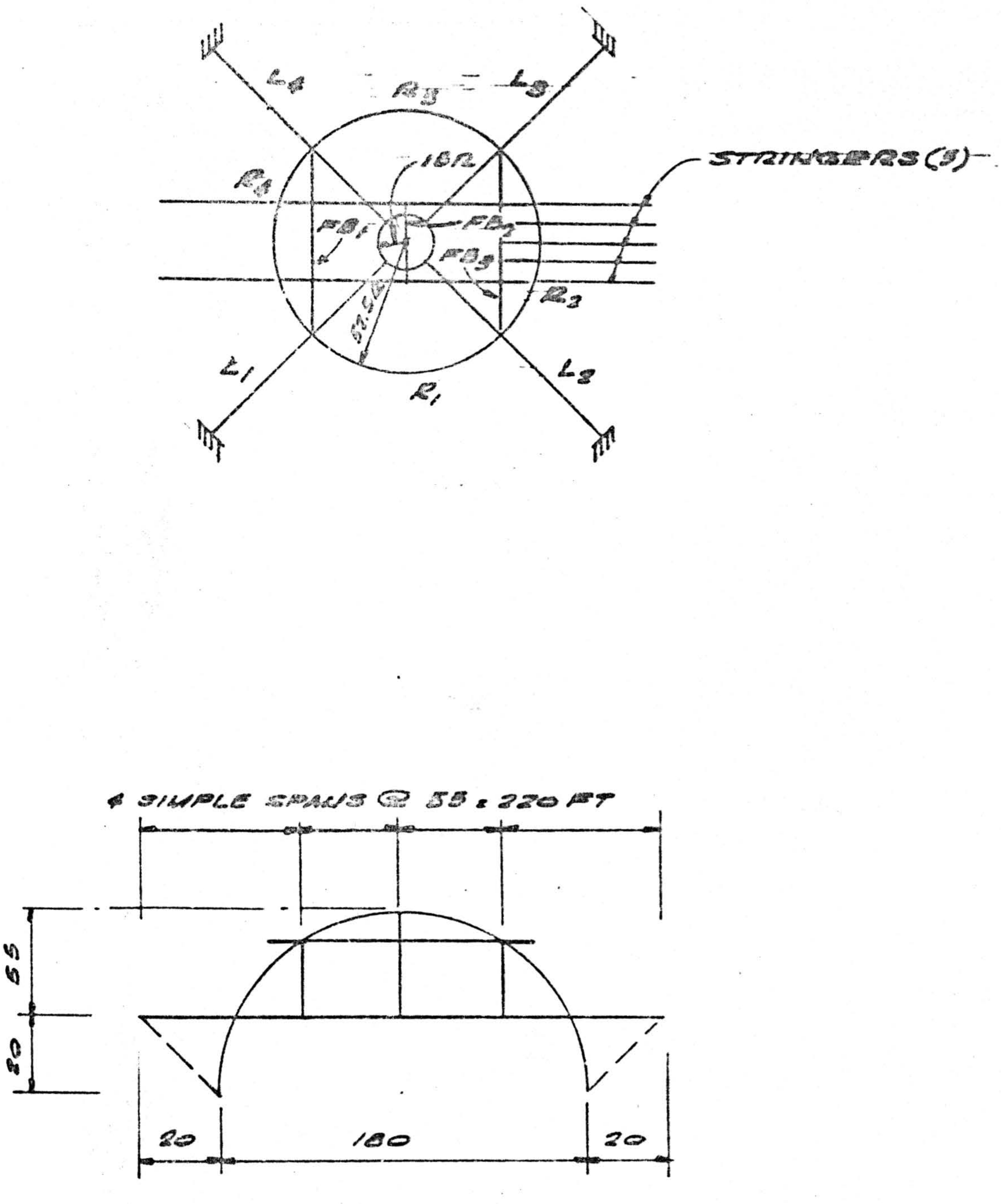


FIGURE 25. BRIDGE CONCEPT NO. 8:
DOME BRIDGE

D. Concept Design Evaluations and Selections for Detailed Analysis

An objective in performing the preliminary analyses and preparing the concept designs discussed in the previous paragraphs was to establish a basis for effecting comparative evaluations necessary for the selection of the most promising concepts. Three means of evaluating concepts were realized. The first was concerned with engineering-oriented appraisals of the efficiency of structural components and systems in responding to load; the second evaluation was based on unit weight estimates which reflect relative economic and more general structural efficiency appraisals. A third means of evaluating concepts (not directly dependent on analysis and design) is more subjective and is principally concerned with aesthetics.

1. Data Summary and Presentation

Table II summarizes the pertinent data and design appraisals for the eight bridge concepts in terms of the comparison parameters introduced above. Aesthetics are a matter of individual judgment, although it is generally agreed that arches and continuous girders are more pleasing in appearance than are frames and trusses. General aesthetic ratings are entered in Column 3. Summary statements concerning design effectiveness are presented in Column 4; bridge system weights (including principal structure, floor system, and total system unit weights) are summarized in Column 5. Since these system unit weights may be considered as indicators of the relative economics of the systems, rankings of the eight concepts in terms of unit weights are presented in Column 6. A remarks column summarizes recommendations discussed in the following.

2. Selections for Detailed Analysis and Design

Design effectiveness, aesthetics, and unit weight considerations combine to indicate that the Leaning Arches Bridge and the Bridle Bridge represent potentially effective concepts for use in new bridge construction. The Leaning Arches Bridge and the Frame Bridge possess capabilities for applications in modifying existing bridges to eliminate hazards presented by massive support structures. Detailed feasibility studies of three bridge concepts (used in the four application modes noted above) were accomplished during the next major effort in the project. Specific concepts selected for preliminary design consideration are presented in Table III. Schematics of the structural schemes developed during preliminary design phases of the program are included as Figures 26 through 29 to make this volume of the report complete as a summary of research efforts. Presentations of artist concept sketches and engineering drawings, design assumptions and criteria, tabulations of key engineering data, and summaries of cost estimates for each of these four bridge concept applications are contained in Volume II (Preliminary Designs and Engineering Data).

TABLE II. BRIDGE CONCEPT COMPARISONS

Concept Identification	Figure Reference	Aesthetics	Design Effectiveness	Weight: Principal Structure	Weight: Floor System	Weight: Total	Weight: Weight per Foot of Bridge	Rank	Remarks
1. "A" Frame	18	Fair	Bending in relatively long frame members and unequal spans reflect ineffective design scheme	211 K	149 K	360 K	1510 plf	7	Deleted from further design considerations
2. Leaning Piers	19	Fair	Effective structure, however, beam-column effect in horizontal girders detracts from structural efficiency	190 K	86 K	275 K	1150 plf	5	Potentially effective new bridge concept and potentially effective concept for modifying existing bridges
3. Braced Arch	20	Good	Discrete point loading of parabolic arch is not most effective use of arch	107 K	101 K	208 K	920 plf	1	Potentially effective new bridge concept
4. Bridle Bridge	21	Good	Potentially effective design scheme; beam-column effect in two horizontal girders detracts from structural efficiency	117 K	66K	173 K	999 plf	2	Selected for preliminary design consideration as a new bridge concept
5. Stayed Girder	22	Excellent	Potentially effective; design optimization can be achieved by changing span length relationships and number of cable ties	111 K	97 K	208 K	1150 plf*	4	Potentially effective new bridge concept
6. Frame Bridge	23	Fair	Relieves ineffective aspects of "A" Frame	165 K	123 K	288 K	1280 plf	6	Selected for preliminary design consideration as a concept for modifying existing bridges
7. Leaning Arches	24	Excellent	Distribution of floor beam loads to many points is efficient utilization of arch	147 K	1102 K	249 K	1130 plf	3	Selected for preliminary design consideration as (1) a new bridge concept and (2) concept for modifying existing bridges
8. Dome Bridge	25	Good	Discrete point loading of arch is not most effective design scheme; arches are relatively long spans	175 K	220 K	395 K	1795 plf	8	Deleted from further design considerations

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*Unit weight computed using effective bridge length of 180 feet.

TABLE III. BRIDGE CONCEPTS SELECTED FOR APPLICATION TO CURRENT PRACTICE

Concepts Applicable to New Bridge Construction	Concepts Applicable to Modification of Existing Bridges
1. Leaning Arches Bridge (Fig. 26)	1. Leaning Arches Bridge (Fig. 28)
2. Bridle Bridge (Fig. 27)	2. Frame Bridge (Fig. 29)
a. Hinged Girder	
b. Continuous Girder	

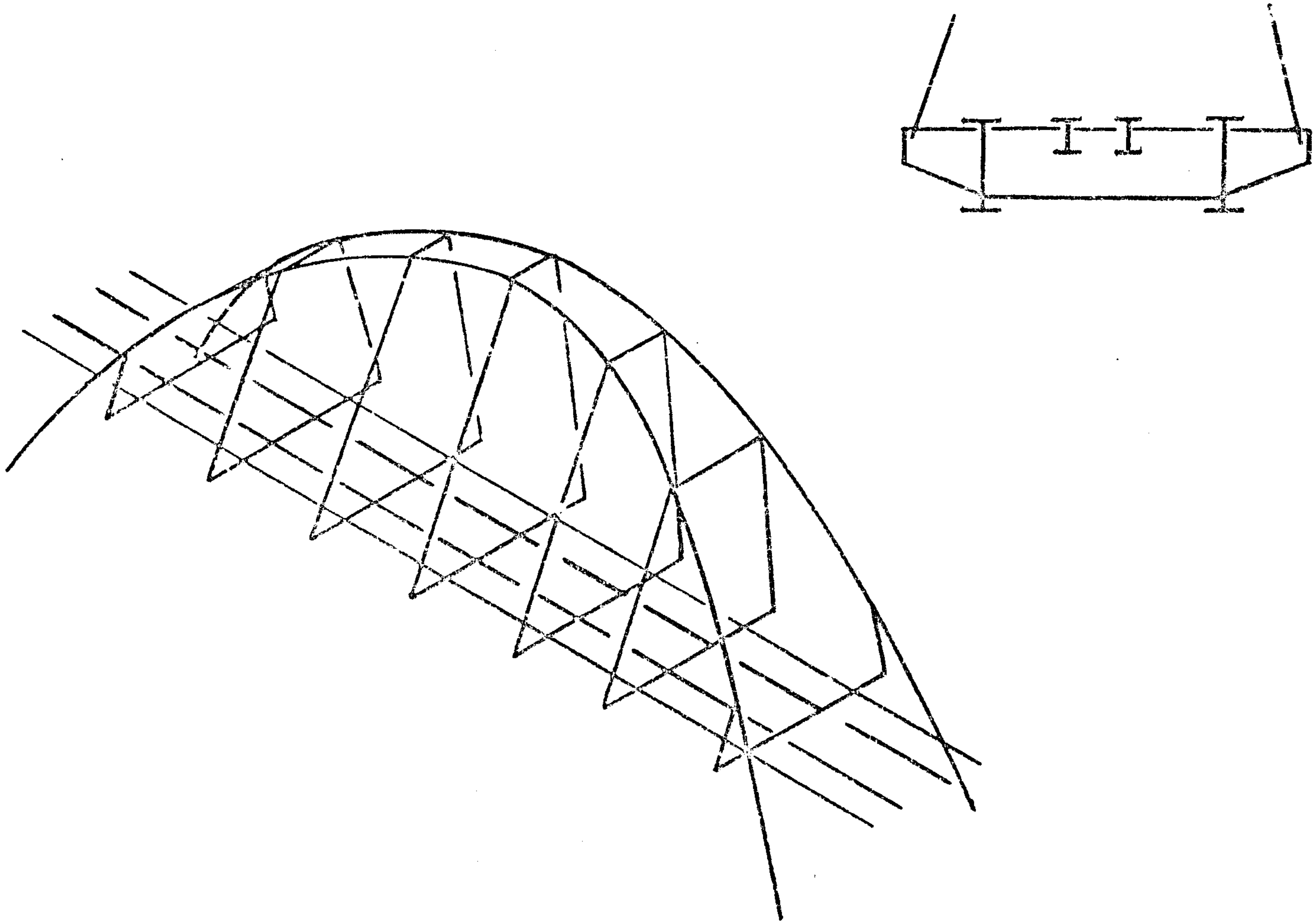

FIGURE 26. LEANING ARCHES BRIDGE CONCEPT APPLIED TO NEW BRIDGE CONSTRUCTION (PRELIMINARY DESIGN CONFIGURATION)

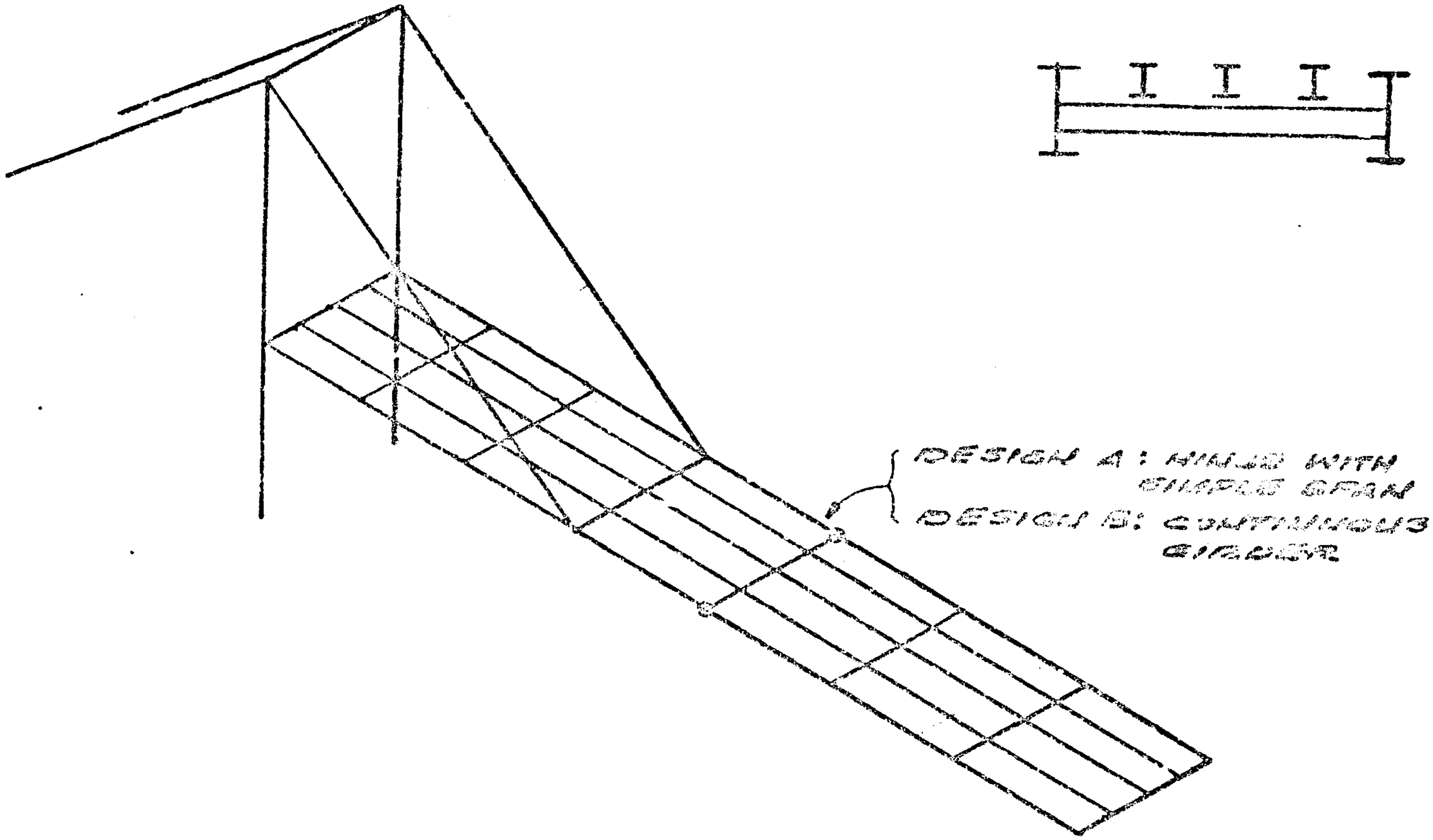

FIGURE 27. BRIDLE BRIDGE CONCEPT APPLIED TO NEW BRIDGE CONSTRUCTION (PRELIMINARY DESIGN CONFIGURATION)

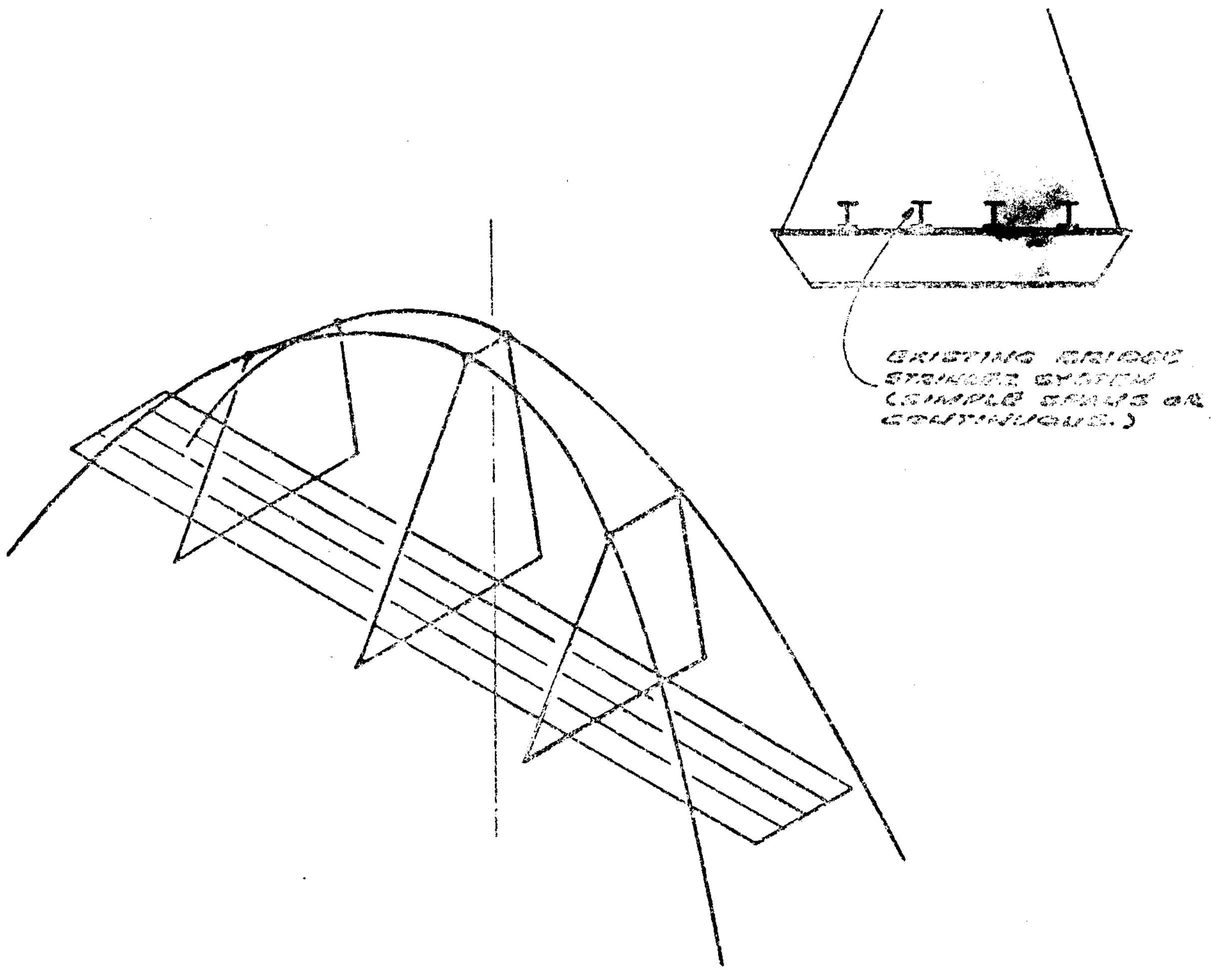

FIGURE 28. LEANING ARCHES BRIDGE CONCEPT APPLIED TO EXISTING BRIDGE CONSTRUCTION (PRELIMINARY DESIGN CONFIGURATION)

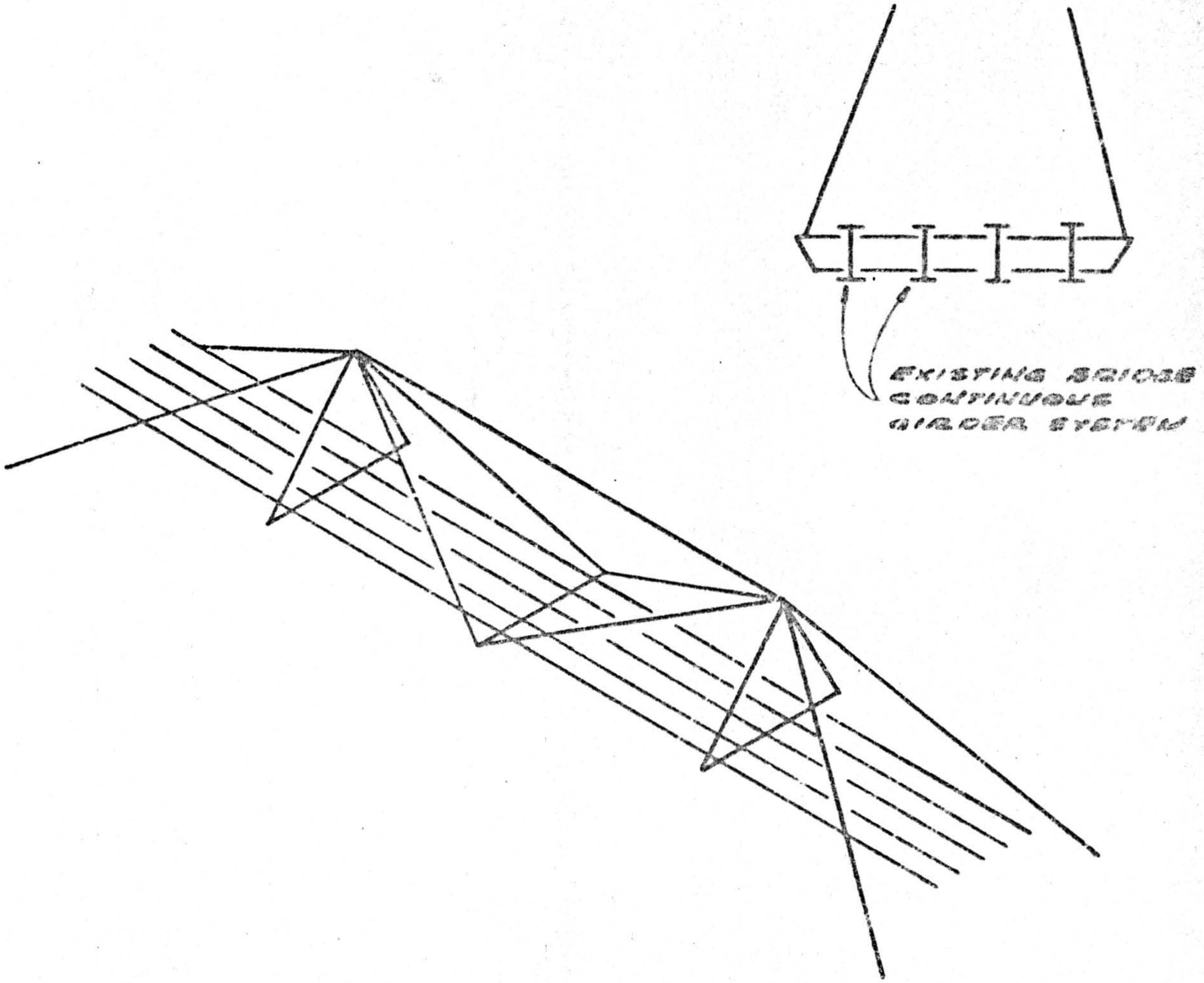

FIGURE 29. FRAME BRIDGE CONCEPT APPLIED TO EXISTING BRIDGE CONCEPT (PRELIMINARY DESIGN CONFIGURATION)

3. Possible Applications of Concepts Not Selected for Preliminary Design

The three bridge concepts identified in Table III were selected for applications studies in the engineering analysis portion of the program. The remaining five bridge concepts were subjected to cursory reexaminations beyond the concept design stage. Based on the availability of concept design evaluations, appraisals were made of the potential applications of these five concepts to the objectives of the program.

The preliminary analysis and concept design studies of the "A" Frame Bridge and the Dome Bridge provide basis for concluding that these two concepts cannot effectively respond to the safety-oriented geometric design criteria (presented in Paragraph B). Concept designs and tabulations of engineering data for these two concepts are recorded in Appendix C of Volume III. Elimination of these two concepts leaves three bridge concepts (Stayed Girder Bridge, Braced Arch Bridge, and Leaning Piers Bridge) which may be considered to be potentially effective structural schemes. While these three concepts were not subjected to subsequent design iterations, they did appear to possess certain capabilities for responding to the safety-oriented design criteria. Possible applications of these three concepts to new construction and modified existing construction are identified in Table IV. Appropriate sketches, tabulations of key engineering data, and design discussions are included for these additional applications in Volume II (Preliminary Designs and Engineering Data), although the data and information are less refined than those presented for applications noted in Table III.

TABLE IV. APPLICATIONS OF ADDITIONAL BRIDCE CONCEPTS

Concepts Applicable to New Bridge Construction	Concepts Applicable to Modifications of Existing Bridges
Stayed Girder	Braced Arch
Braced Arch	Leaning Piers
Leaning Piers	

IV. SIGN AND LIGHTING SYSTEM SUPPORT STRUCTURES

New concepts for structural supports of highway signs were limited to consideration of overhead, as opposed to roadside or ground, mountings*. This definition of scope reflected the observation that roadside or ground-mounted signs can be essentially eliminated as a safety hazard by relocation outside of the 30-foot clearance line or by design as "breakaway" structures. Therefore, attention in this section of the report was devoted specifically to the massive support structures identified with two types of overhead sign structures: cantilever and overhead.†

As a technology, lighting systems for highways are in a state of flux. High intensity, mercury vapor lamps, for example, provide a new dimension in highway lighting. Conventional 400-watt lamps (mounted on 30- to 40-foot light standards and spaced 200 feet apart) satisfy illumination requirements(4) but they impart "tunnel vision" and, in some cases, cause veiling glare due to direct visibility of the lamps as well as reflected light. The trend toward 1000-watt luminaires as a means of reducing tunnel vision and glare requires a higher lamp placement (up to 60 feet) and increased spacing (from 300 to 350 feet). While heavier lamps on taller supports require more massive structures that present more hazardous obstacles to errant vehicles, this disadvantage is partially offset by a decrease in probability of collision as a result of increased spacing. The economic advantages for supports over 60 feet high may be offset, however, by increased service and maintenance problems.

A. Sign Support Structures

Establishment of criteria to govern design of overhead sign support structures which are responsive to the objectives of this study began with a review of current design standards. Current practice is represented by three AASHO documents (References 1, 3 and 5).

As in the case of the bridge studies, criteria for the design of sign support structures may be divided into three areas: geometry, load, and aesthetics. With respect to geometry, the AASHO specification states that ". . . it is advisable to provide greater vertical clearance for sign bridges (than for other roadway structures) . . . ." With this requirement in mind,

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*By definition, the sign is the panel on which the message is displayed; the structure supports the panel and resists design loads.

†These types of sign support structures are identified in "Specifications for the Design and Construction of Structural Supports for Highway Signs," AASHO, 1961(3).

projected geometric requirements for sign structures were established as shown in Figure 17, with the exception that the required vertical clearance must be 18 feet over a width of 170 feet, rather than the 17 feet noted for other roadway structures. Other geometric considerations pertain to the horizontal clearances required for exit and entrance ramps, and near access roads (e.g., sign structures supports should not be placed in a "gore" area). However, the geometric standards related to horizontal clearances are sensitive to characteristics of a given site. Accordingly, for the purposes of concept development and application feasibility studies performed under the BPR program, it was deemed advisable to adopt a representative horizontal clearance as shown in Figure 17.

Load requirements for overhead sign supports are detailed in the AASHO specifications for the design and construction of structural supports for highway signs(3); these include dead, live, ice, and wind loads. The first two involve structure weight and walkway forces, respectively; the latter two are concerned with forces which vary according to geographic area and require detailed analysis based on ice weight and wind pressures. For the purpose of evaluating conceptual designs of sign supports, these load conditions were simplified into a representative load* requirement which was applied to each concept. This representative load consisted of an estimated combined dead and ice, and wind load computed using a wind pressure of 55 psf, suitably modified by supplementary factors for application to structural members. In addition, the wind loads were considered to act normal to the vertical face of the sign and support.

The aspect of aesthetics is covered in current standards by general statements and guidelines. In the AASHO specification, for example, it is noted that "within the limits of practical economics and with primary regard for the utility function performed by overhead sign supports, features which promote the aesthetics of such structures should receive proper attention . . . ." A specific guideline states, "Aesthetics will be improved if the upper and lower edges of two or more sign panels on a single overhead sign structure produce parallel horizontal lines." As in the case of bridge concepts evaluation, sign structure aesthetics were given a qualitative role in the appraisals of concept designs.

1. Sign Structure Concepts

New sign support concepts can be placed into a context compatible with definitions of sign-supporting structures contained in AASHO specifications. These concepts are shown in Figure 30 and are identified as

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*Ross and Olson(6) have concluded that this statically applied load is unconservative and that new design criteria should be developed for highway signs.

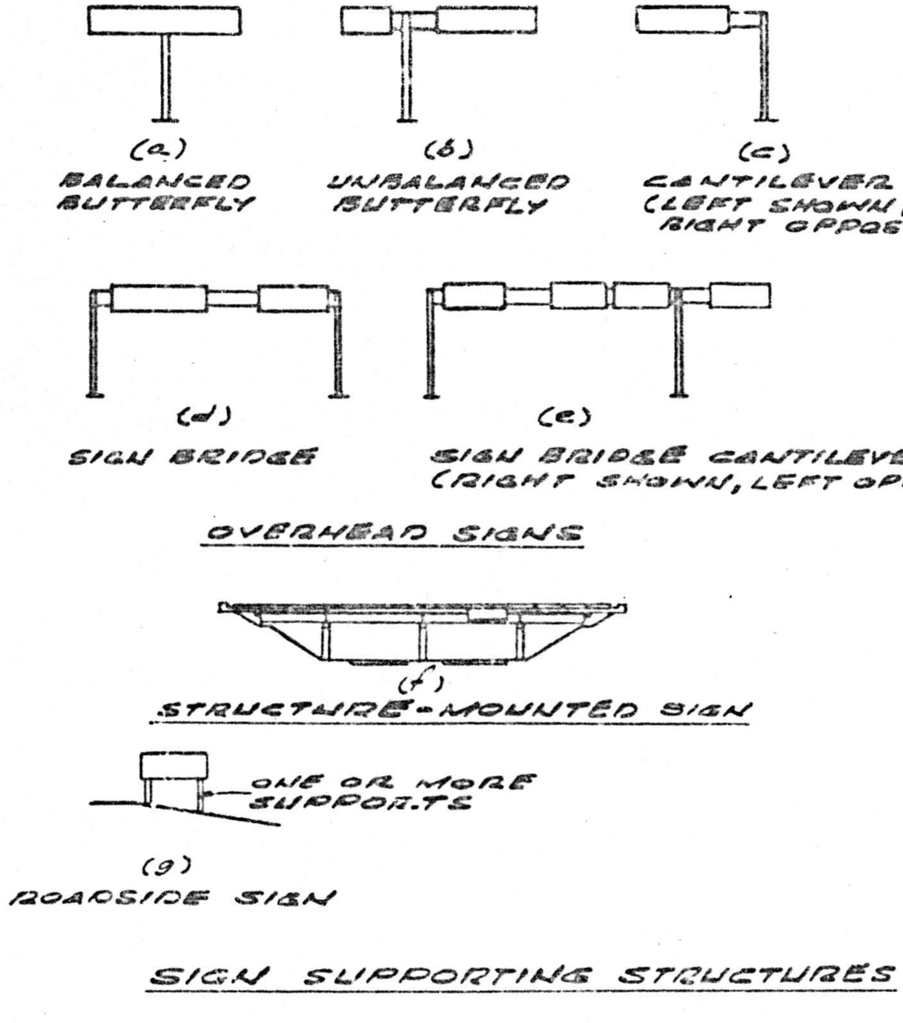


FIGURE 30. CURRENT SIGN SUPPORTING STRUCTURES (FROM REF. 3)

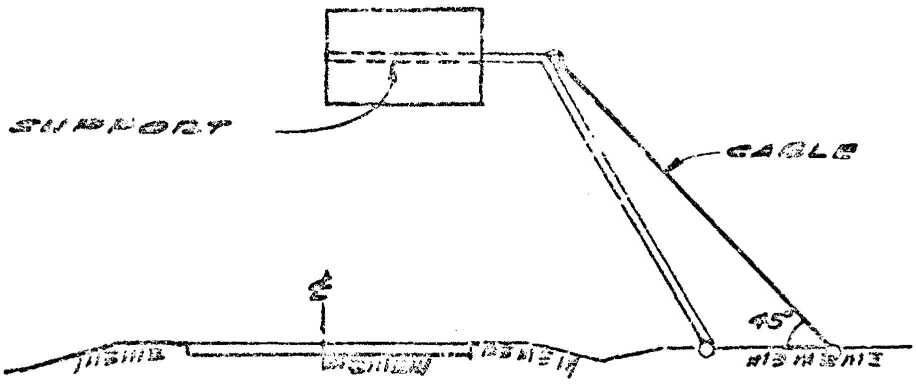
follows: (a) balanced butterfly, (b) unbalanced butterfly, (c) cantilever, (d) sign bridge, (e) sign bridge cantilever, (f) structure-mounted sign, and (g) roadside sign. The two butterfly designs should not be used in new construction (and, where possible, they should be removed from existing construction) because their design application calls for placement in a "gore" area or in an area that must be in close proximity to a travel way. The sign bridge cantilever should find no future application for the same reason. Structure-mounted signs are not within the scope of this study, although it is noted that use of bridge structures for signing purposes is probably not as prevalent as it should be. Roadside signs do not present hazardous massive support structures if they are positioned away from proximity to the travel way, or if they are configured to be of breakaway design. Thus, the remaining structures (i.e., the cantilever and the sign bridge) are the only types of sign supports requiring efforts directed toward the elimination of massive structures.

A cantilever support concept (such as shown in Figure 31) may be employed for a sign over a single, outside traffic lane or a single ramp lane, and comply with the geometric requirements previously outlined. The bridge type of sign support structure may also be designed in a manner responsive to projected geometric requirements by using an overhead cable suspension system (Fig. 32), a guyed arch (Fig. 33), or a guyed frame (Fig. 34). These four sign-support concepts were evaluated; the results are discussed in subsequent paragraphs.

2. Analysis and Concept Designs

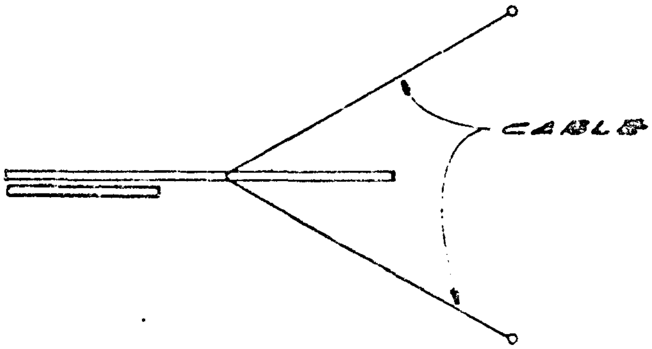
The two types of sign support structures that are responsive to projected geometric requirements (i.e., the cantilever and the sign bridge) are subjected to demanding design conditions. In the case of the cantilever design, an arm on the order of 35 to 40 feet long will be required to effect the necessary clearance and to obtain an optimum overhead sign position. This condition will bring about large torsional moments at the cantilever support point. Sign bridge geometric requirements (which assure 30 feet of clearance on either side of the travel way shoulders) dictate a span of 170 feet if the sign bridge must span both travel ways of a divided highway with a 60-foot wide median. Longer spans will be dictated by multilane travel ways (six lanes or more) with medians 60 feet or less in width.

Current sign structures are proportioned to avoid resonant conditions at critical wind speeds by limiting their vertical deflection. The severe reach and span requirements imposed on the cantilever and bridge types of sign support structures, and the inherently flexible nature of the cable-supported design schemes, indicate that some difficulty will be encountered in satisfying current deflection specifications with projected structures. If effective design schemes using cable-supported structures are to be realized, the current deflection restriction must be relaxed. This may be



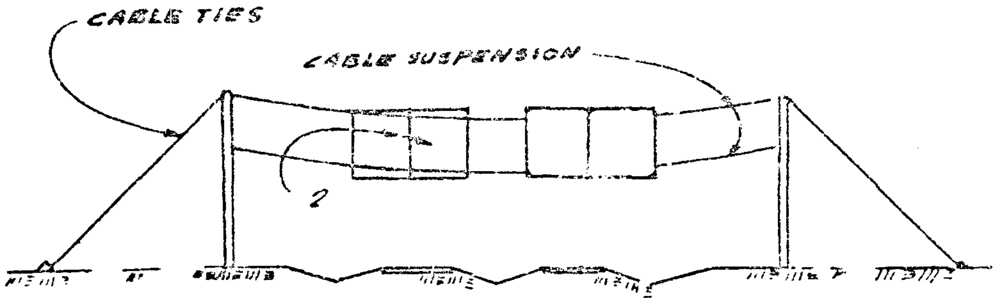
ELEVATION

NOT TO SCALE



PLAN

FIGURE 31. GUYED CANTILEVER SIGN SUPPORT STRUCTURE



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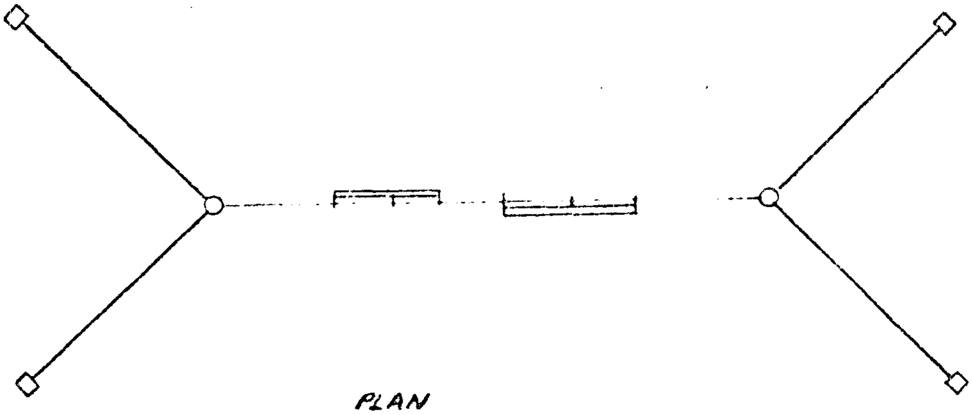
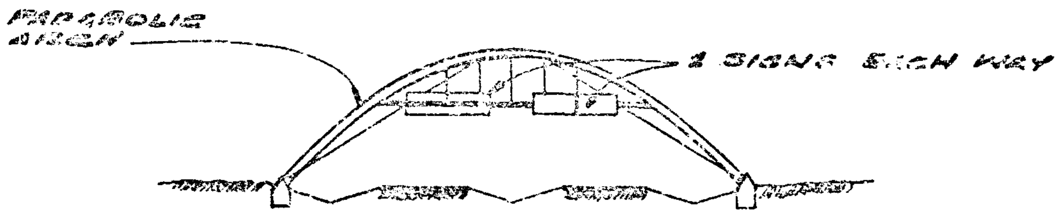


PLAN

FIGURE 32. CABLE SUSPENSION OVERHEAD SIGN SUPPORT STRUCTURE



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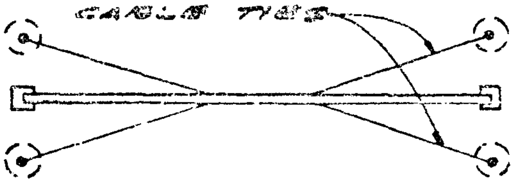

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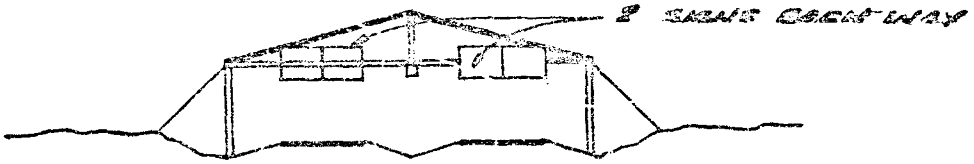
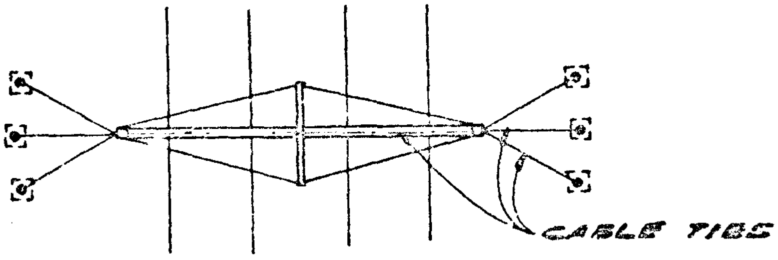
FIGURE 33. GUYED ARCH OVERHEAD SIGN SUPPORT STRUCTURE



ELEVATION



PLAN.

FIGURE 34. GUYED FRAME OVERHEAD SIGN SUPPORT STRUCTURE

achieved by establishing some other less restrictive parameter for avoiding dynamic instability or, preferably, providing the designer with methods for conducting a simplified dynamic analysis. Dynamic analyses were not conducted in the initial evaluations of the four concepts; final determination of a concept's total application and cost effectiveness can be accomplished only by establishing basic dynamic properties of the systems (e.g., natural frequencies of vibration).

The above observations point out major problems encountered in attempting to provide effective, safe sign systems. Research is being accomplished in areas concerned with information dissemination techniques which will relieve these problems by eliminating the conventional sign; techniques such as holography or radio-transmitted voice directions are examples of alternative methods for directing traffic flow. Structural support systems that are responsive to projected geometric and dynamic stability demands may be such as to suggest that alternative methods may indeed be the answer; however, it is the purpose of this effort to develop the most effective sign support techniques for the indicated spans. In the paragraphs that follow, structural systems that may be employed to effect optimum sign position above the travel way and maximum safety are discussed.

• Guyed Cantilever Sign Support Structure

The design scheme presented in Figure 31 illustrates a simple method for providing a single 6-foot by 10-foot sign over the outside lane while maintaining horizontal clearance geometric requirements. Although simple in appearance, the structure is not simple in design. Design calculations indicate that the torque at the cantilever support point is significant, and, because the tripod formed by the compression members and two tension members cannot effectively resist this torque, it must be carried to the ground via the vertical member.

The concept design resulting from a static load analysis of the guyed cantilever sign support structure does not appear particularly heavy or out of proportion. Deflection calculations and preliminary dynamic analysis, however, indicate that this structure must be subjected to additional studies, prior to finalizing the design. Alternate concept designs include configurations with taller legs to permit support of the sign from the top. Sway bracing, such as is found in certain current light supporting arm designs, also may be employed. Appraisals of the concept design indicate that the relatively long reach required by projected geometric standards, coupled with the large drag-type structure presented by the sign itself, may preclude effective use of this type of sign support structure. Additional attention, particularly in the area of dynamic analysis, must be given to the cantilever type of sign support concept.

- Cable Suspension Overhead Sign Support Structure

The concept illustrated in Figure 32 was included because it constitutes the most obvious use of cable systems as a solution to providing safe sign support structures. Although the static load analysis of the support structure is straightforward, it is obvious that the system may become dynamically unstable in a vertical plane coincident with the signs, in a torsional mode about the signs' horizontal axes or in a transverse mode parallel with the axis of the roadway. Basically, it was for this reason that the design was not carried beyond the conceptual stage. Furthermore, the sag in the cable-supporting members and the broken lines caused by ties to the vertical members were deemed to be aesthetically unsatisfactory for even the least demanding highway locations.

- Guyed Arch Overhead Sign Support Structure

Preliminary analyses of the overhead sign support concept shown in Figure 33 indicated that the design is relatively effective and is aesthetically pleasing. Signs could be attached to the arch in a manner which uniformly distributes vertical loads. Cable ties permit the structure to resist a wide range of forces applied out of the plane of the arch, provide lateral stability, and minimize horizontal bending in the arch.

Arch structures with required spans will be relatively light and aesthetically pleasing. As was the case in other sign support concepts, structural dynamics represent an aspect that cannot be overlooked; however, there seems to be a greater opportunity for minimizing the adverse effects in the guyed arch overhead sign support structure.

- Guyed Frame Overhead Sign Support Structure

The guyed frame concept (Fig. 34) represents an attempt to stabilize a long span, light truss, or space frame structure by use of cable guys. Cable ties in a horizontal plane (which frame to a horizontal strut) provide stability of the superstructure in a direction parallel to the axis of the roadway. Additional cable guys stabilize the vertical supporting members.

Analysis of this concept indicates that the structure is quite flexible and would probably present severe dynamic stability problems in several modes. The planar truss configuration shown would not prove to be adequate because of the extremely long compression strut. An alternate design involving a stabilized space truss seems to be a potential improvement; nevertheless, the structural dynamics of this scheme would have to be closely examined.

3. Sign Support Structures Evaluations and Preliminary Designs

Evaluations of concept designs in the cantilever and overhead (bridge) sign support categories were unavoidably influenced by considerations of other research and development efforts. When the review of concept designs was accomplished by project technical monitors and principal investigators for the purpose of selecting structural schemes for further study, the guyed cantilever was chosen as being the most promising candidate for the solution of existing problems and, for this reason, was given additional, preliminary design consideration. A detailed analysis and design iteration, following as closely as possible the "Specifications for the Design and Construction of Structural Supports for Highway Signs,"(3) reveals that the design is not necessarily structurally effective. Depending on the specific dimensional characteristics and preload condition of the cantilevered structure, it is possible for the cables to introduce unsymmetrical forces sufficient to induce buckling failures. One approach to providing the increased resistance to transverse loads (a primary function of the cable system) is to introduce a pre-tension sufficient in magnitude to assure that the total of the cable forces will remain constant. Stated differently, if the tensile forces imposed by the cables are preselected such that under wind loading no cable experiences a zero load condition it is possible to design the main cantilever structure to preclude the possibility of a buckling failure. Involved is a tradeoff between an increase in transverse dynamic stability and the offsetting disadvantages of: (1) bending stresses that are additive to those induced by dead loads, and (2) a propensity toward buckling--both of which increase the structure's size and analytical complexity. A cantilever sign support structure was designed as shown in Figure 35. Specifications for including dynamics in the analysis by employing a dynamic load factor were used in achieving a preliminary design. However, because sign dynamics will become increasingly important as safety criteria are met, a method for the dynamic analysis of such systems should be developed.

B. Lighting System Support Structures

High-level lighting systems, involving 100-foot light support towers, are currently being evaluated for use at such locations as the intersections of interstate highways. Systems have been specially designed for accomplishing servicing and maintenance, and are expected to provide optimum vision for the motorist in terms of perspective and reduced glare. This new tower lighting trend is expected to be a long-range future application; thus, it is considered to be outside the scope of this study. Likewise, considerations of the lamp parameters related to illumination (e.g., diffusers, aging, efficiency, uniformity, brightness, etc.) were not included in the scope of this study.

Use of a frangible aluminum casting at the base of 400-watt light supports has proven effective in reducing injuries resulting from errant

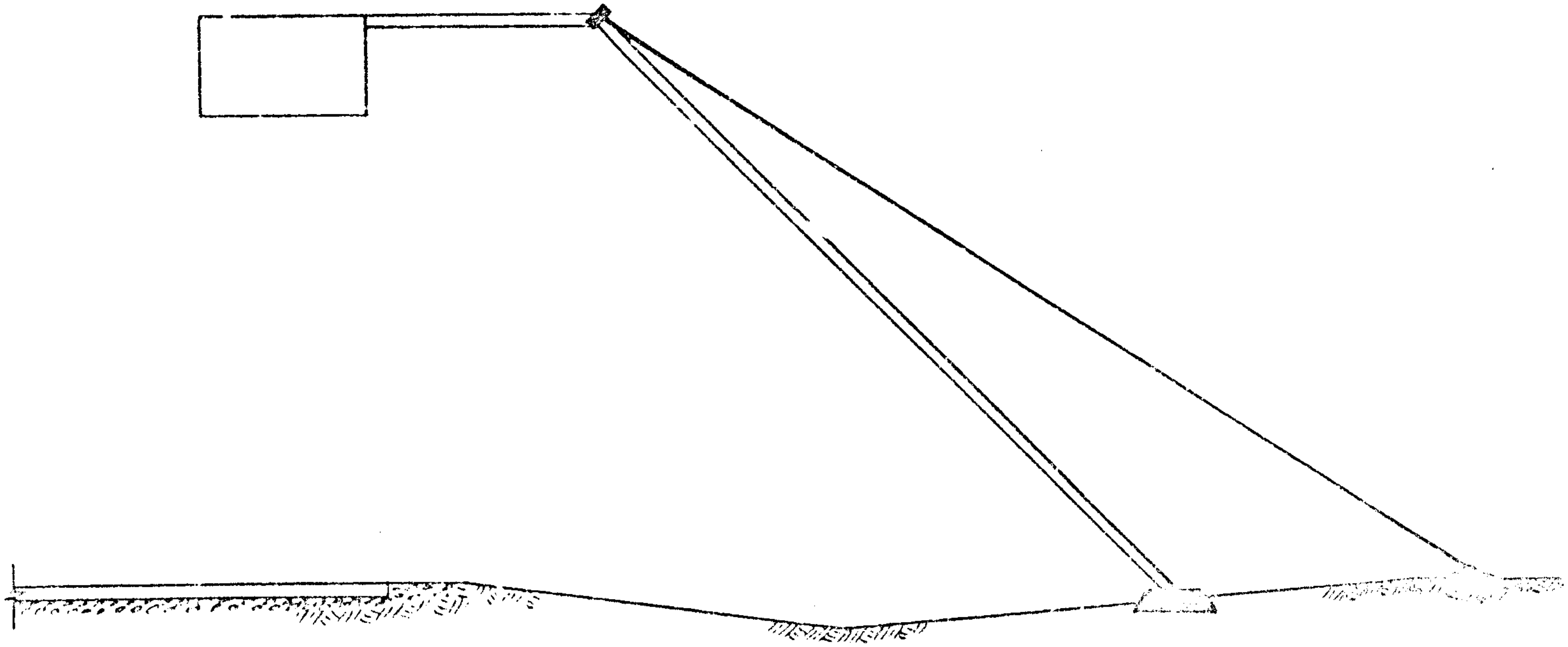


FIGURE 35. SIGN SUPPORT STRUCTURE CONCEPT
(PRELIMINARY DESIGN CONFIGURATION)

vehicles impacting light supports structures; however, the applicability of this technique to supports that are 50 feet or more in height has not been established.

This section of the report, however, is concerned with efforts directed toward developing light support concepts which will permit removal of massive support structures from proximity to the travel way. The use of some form of cable support system appeared to present a most promising potential. Various types of cable systems for supporting lighting systems that are responsive to program objectives were developed, analyzed and evaluated.

The geometry for present-day lighting systems is based on roadway illumination and uniformity requirements which are provided by conventional 400- to 1000-watt mercury vapor lamps positioned 30 to 60 feet above the edge of the roadway at intervals ranging from 150 to 350 feet. To replace the vertical support, whose base is normally immediately adjacent to the shoulder, various cable systems have been studied and analyzed.

Load design criteria for lighting system support structures include: (1) the dead load of the lamp plus its support superstructure, (2) the dead load due to ice, and (3) wind live load, as applicable for the geographic area. The deflection criteria for light supports are not as restrictive as for sign supports and generally allow deflection up to 10 percent of the support length for aluminum and 5 percent for steel. Materials criteria embody stress allowables and weatherability. Materials selection embodies evaluation of many factors, including site conditions.

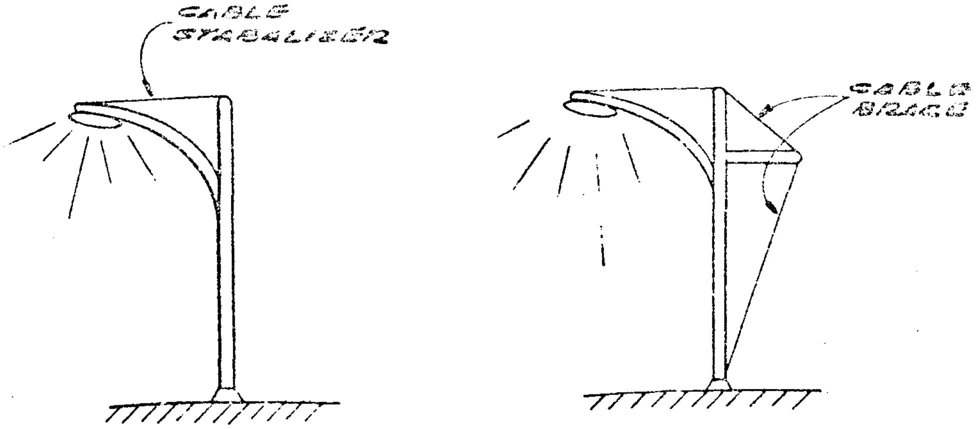
Since the frangible base technique has proven to be an effective means of minimizing the severity of the collision hazard for 400-watt lamp supports, concept development attention was directed toward development of cable systems to support 1000-watt, 50-foot-high lamps.

1. Lighting System Support Structures Concepts

Present-day lighting supports that properly position the lamps can be grouped in two general categories: cantilever-supported and overhead-supported. The cantilever-supported category embodies the discrete, free-standing structures (including the currently used pole-arm unit). The overhead-supported category includes bridge structures, as well as cable suspension systems.

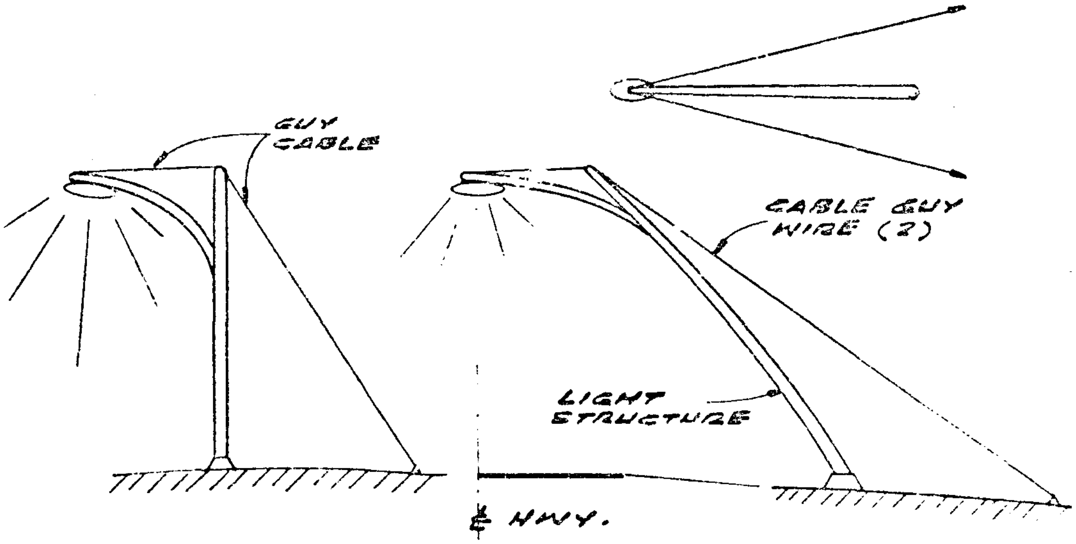
Cantilever-Supports

The sway bars employed in current designs effect stabilization of the dead load and wind load deflections and could be replaced by cable stabilizers (see Fig. 36) to reduce flexural stresses as well as



(a) CABLE STABALIZED LIGHT SUPPORT

(b.) CABLE BRACED LIGHT SUPPORT



(c) CABLED GUYED LIGHT SUPPORT

(d) CABLE GUYED LIGHT SUPPORT PROVIDING ADDITIONAL CLEARANCE

FIGURE 36. TERMINOLOGY OF CANTILEVER CABLE SYSTEMS FOR LIGHTING SUPPORTS

distortions in the cantilever arm. This modification appears to be the appropriate step to provide longer cantilever arms required by additional setback clearances from the travel way. Torsional distortions could be reduced by spiral cable wrap (around the vertical column), anchored to the support foundation. Cable-braced and cable-guyed supports (see Fig. 36) are, in a sense, logical extensions of the cable-stabilized system except that the cable extends and ties to the foundation in a manner that reduces flexure in the column. Cable guys (see Fig. 36)(common in overhead electrical transmission systems) have not found acceptance for highway lighting structures despite obvious structural advantages. Principally, the poor aesthetics, the additional obstacles presented by guy anchorages, and the additional space required (which could necessitate additional ROW procurements) combine to make this concept unacceptable.

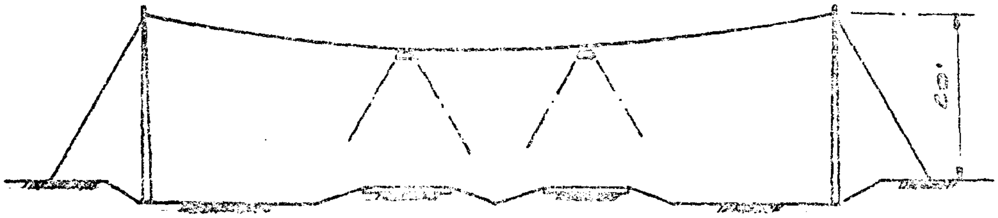
Overhead-Type Supports

Bridge-type structures to support lights are feasible; however, unless the cantilever arm proves to be structurally inefficient, a bridge does not seem warranted for 50-foot-high lamps. For special cases, concepts similar to those for sign bridges could be employed.

Suspension systems of either a discrete type or a continuous type (see Fig. 37) could be more applicable for lighting systems than for signs. Because the lamps are smaller and lighter, do not have to be as dynamically stable as signs, and need to be spaced in multiple arrays, the suspension systems appear to be worthy of consideration. In heavy traffic urban areas with extensive lighting requirements, the continuous-type cable suspension system may offer some advantage in multiple lamp placement; however, this advantage is not present for the high-intensity lamps with wide spacing. For wide median areas, a discrete suspension system may be particularly desirable to support a luminaire over each roadway, ramps, emergency stop zones, etc., in order to not create a massive structure in the "gore" area.

2. Analysis and Concept Designs

An analysis of the loads, moments, and torques was conducted for a cantilever light support having conventional geometry, but with a 30-foot setback and a 50-foot luminaire height. The resulting concept design consisted of 6-inch standard pipe, 30 feet long, with a horizontal arm attached to a 10-inch-diameter vertical column. This support would weigh about 2500 pounds and would employ no cable system. While such a support is aesthetically appealing, it is not structurally efficient. With guy cables, a 6-inch-diameter straight pipe could be used for the column, and, if cable stabilizers (or sway bars) were used, the horizontal arm could be only a 3-inch-diameter pipe, thus reducing the overall structural weight by about



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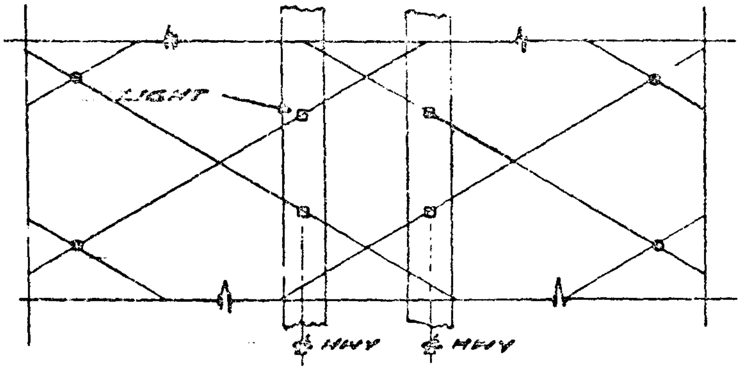
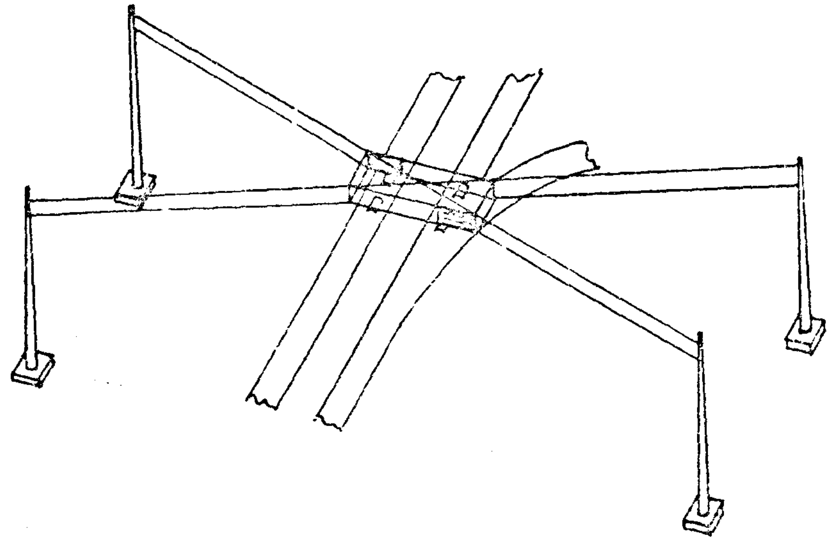


PLAN

(1) CONTINUOUS SYSTEM



(2) DISCRETE SYSTEMS: EXITS & INTERSECTIONS

FIGURE 37. CABLE SUSPENSION SYSTEMS FOR LIGHTING SUPPORTS

1400 pounds. These concept designs were developed by employing a static analysis; however, a dynamic analysis will be required to fully evaluate the feasibility of a given structural configuration.

A similar system analysis and concept design was accomplished for a cable suspension system light support. This design minimizes the obtusiveness of the cables; however, they would be visible. The previously noted trends toward area lighting at intersections and ramp areas minimizes the potential effectiveness of this type of lighting system support structure.

3. Lighting System Support Structures Evaluations and Preliminary Designs

Good illumination levels and uniformity can be provided with lighting system supports placed 30 feet from the edge of the traffic lanes. On the other hand, the concept designs indicate that the structures will be relatively massive and expensive. Cable support systems could reduce the massiveness and cost of providing the 30-foot setback at some sacrifice to the aesthetics, and if dynamics were considered and found to be acceptable. Whether or not these considerations will be acceptable or not will depend on judgment. Compromise solutions that are more aesthetically appealing and employ some of the structural efficiency of the cable systems may be obtained by additional attention to details.

Evaluations of concept designs in the cantilever and suspension lighting system support categories were governed by the same types of considerations found to be present when evaluations of sign support structures were conducted. Research by others in area lighting concepts tends to obviate the need for the suspension type of lighting support system. When the review of concept designs was accomplished by project technical monitors and principal investigators, the guyed cantilever scheme was chosen as the only concept worthy of further study.

The cantilevered lighting system support structure (see Fig. 36d) was selected as the basic scheme to receive additional consideration in the detailed analysis portion of the program. As in the case of sign support structures, cable guys were found to be desirable. Pre-tension in the cables would reduce dead load bending stresses and would have the same potential advantages discussed in applying this concept to sign structures (ref. Paragraph IV. B. 3). Accordingly, the lighting system support structure was considered as a guyed cantilever, as shown in Figure 38, for luminaire heights above the roadway of 40-, 50-, and 60-foot mount heights. Volume II of the report contains detailed preliminary design data and engineering drawings; supporting information pertaining to analysis and design is included in Volume III.

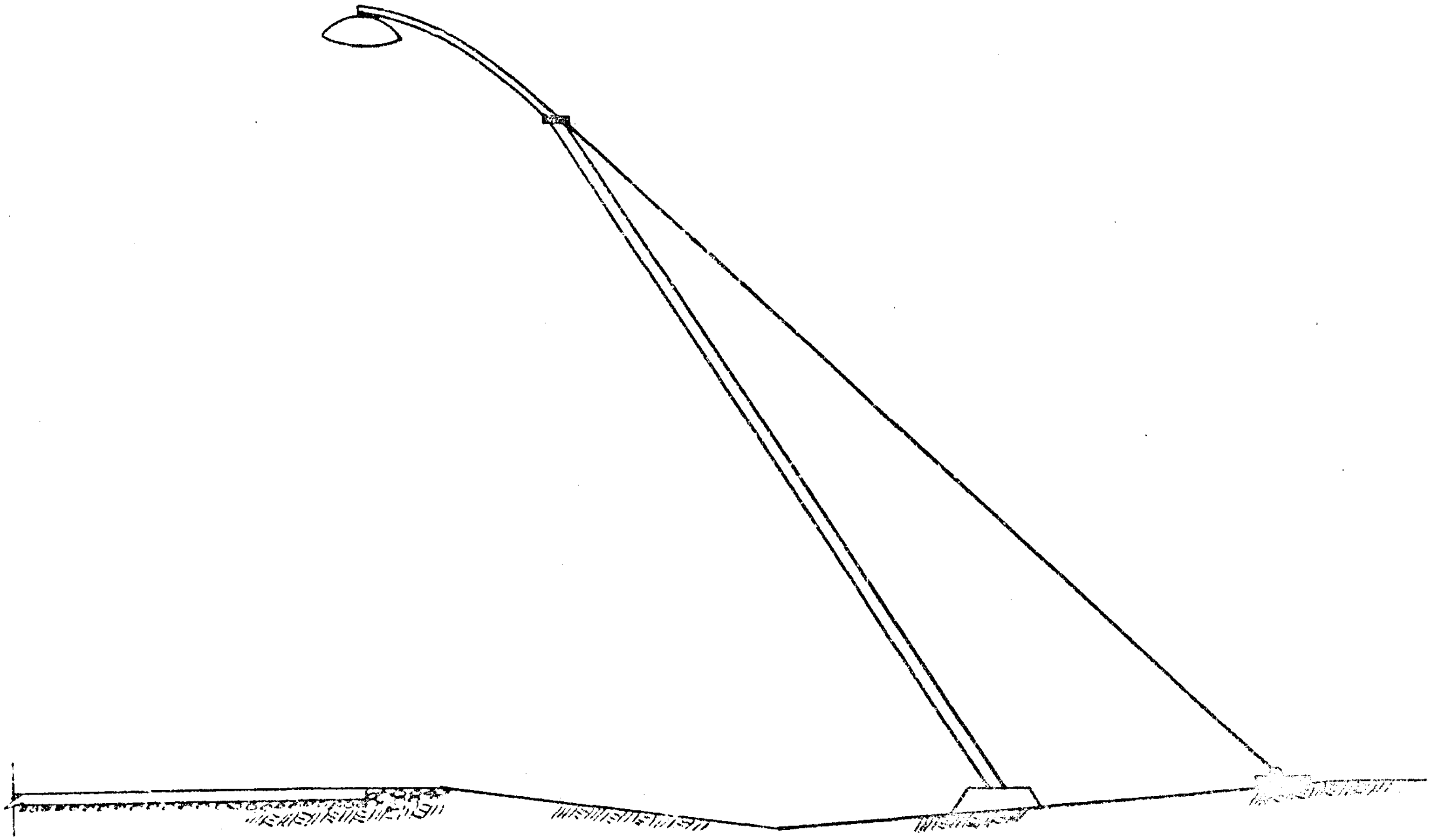


FIGURE 38. LIGHTING SYSTEM SUPPORT CONCEPT (PRELIMINARY DESIGN CONFIGURATION FOR 50-FOOT LUMINAIRE HEIGHT)

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