

## KINETIC BRIDGES

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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## ABSTRACT

This report on kinetic bridges is essentially a state-of-the-art study on two types of bridges whose location or physical characteristics are designed to be time dependent.

The first type, called a "relocatable bridge", is essentially for use as a temporary structure that must be erected quickly. Many recent examples of this type are described, ranging from the familiar Bailey Bridge now in common civilian use, to the high technology Armored Vehicle Launch Bridge being developed for military use.

The second type, called an "actively controlled bridge", is a newly emerging type of structure whose strength and load-induced deformations can be controlled automatically through a system of sensors, analyzers, and energizers. This report summarizes recent developments of this bridge type and suggests directions where application may be desirable on future bridges, particularly long-span ones.



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## INTRODUCTION

Kinetic bridges are defined as bridge structures whose location or physical characteristics are designed to be time dependent. As pertains to vehicular bridges, they are represented by three basic types called "moveable", "relocatable", and "actively controlled".

Moveable bridges are a type in which a span, or a portion of a span, can be moved out of the way for the passage of something too large to safely pass through or beneath. Most moveable bridges are located over navigable waters and are moved for the passage of a vessel or barge. A few are designed to be moved to prevent flood damage. The latter are constructed so they can be rolled back on land out of the way during a flood.

Moveable bridges are of four types: bascule, swing, lift, and retractile (or retractable). The bascule bridge is basically a cantilever structure that can be pivoted upward about a horizontal axis at one end. The swing bridge is also a cantilever structure and can be rotated horizontally about a vertical axis. The lift bridge is a simply supported span that is lifted vertically on towers at each end. The retractile bridge is one in which the moveable span slides essentially horizontally and in line with the roadway. Variations of both the retractile and swing bridge type can be found as floating (pontoon) bridges.

In the main, this report will not deal with moveable bridges to any degree as there is a trend away from their use toward that of fixed high level bridges. For this reason, no major breakthrough research for moveable bridges is seen at this time. Improvements, however, are being made in certain features as hydraulic machinery and electronic control systems on the moveable bridges that are used; but the basic structural concepts remain essentially unchanged.

Relocatable bridges are those which can be easily moved from site to site and which may be adaptable to accommodate different spans or loads. A number of this type of bridge are in use; however, none may be considered ideal, and further research and development on this type is warranted. This report will describe the many new types developed in the last forty years and will suggest possible future developments.

Actively controlled bridges are those whose strength- and load-induced deformations can be controlled automatically through a system of sensors, analyzers, and energizers. At present, this type of kinetic bridge is only a theoretical concept which shows promise for the future. This report will summarize recent developments of this bridge type and give direction to possible future developments.

The report basically represents a state-of-the-art study augmented by some suggested future developments. Its purpose is to acquaint readers with a little understood form of bridging and to encourage development of kinetic bridges. Because of their desirable adaptable features, their use will undoubtedly increase as development increases.

### RELOCATABLE BRIDGES

There are many needs for relocatable bridges, most for situations where a quickly erectable temporary bridge is required. These situations include detours, as when a permanent bridge or roadway is being built or repaired; disasters, as when a bridge is destroyed by flood, accident or war; off-road sites, as when access by utility or military vehicles or personnel is required; and where reinforcing is required, as when a weak bridge has to be strengthened temporarily for the passage of an overload.

The lack of a bridge in a transportation network can be extremely disruptive and expensive in terms of time, energy, and money; and in some cases perilous to life and health as well. Because of these factors, relocatable bridges must be capable of being taken out of storage and erected on a site quickly. As virtually every site and traffic situation is unique, such bridges must be adaptable in adjusting to a wide variety of span lengths and load conditions. Prefabrication in some form is absolutely essential. Furthermore, as relocatable bridges are generally temporary, they must have the capability of being dismantled or retracted easily, so that they may be used at different times and places. Because a relocatable bridge has many special features not found in a conventional bridge, its cost must be balanced against the time, energy, and money lost by the user in not having it available.

The following is a description of thirteen relocatable bridge types which meet, in various degrees, the criteria described above.

### Bailey Bridge

The Bailey bridge, developed by the British in World War II, is perhaps the most well known of all relocatable bridge types. Designed by Sir Donald Bailey as a military bridge, it has been used around the world for both military and civilian purposes. Its use at this time is primarily by civilians. The Virginia Department of Highways and Transportation has a number of Bailey bridges for H15 loading stockpiled for emergency use. New types of military bridges have since been developed which, for the most part, have replaced the Bailey bridge. (These new military bridges are described later in the report.)

In concept, the Bailey bridge is a one-lane structure consisting of prefabricated components of steel that can be pinned and bolted together in a wide variety of span lengths and strengths. Spans as great as 200 ft. for an AASHTO loading of HS15 can be attained. For an HS20 loading, spans up to 180 ft. can be had. The basic unit is a trussed panel, approximately 10 ft. long and 4 ft. 9 in. high and weighing 577 lb. Panels can be joined together longitudinally, vertically, or laterally in various combinations to form the basic longitudinal bridge trusses. Prefabricated transverse floor beams or transoms connect the flanking trusses to support the bridge deck. The deck can be either prefabricated metal grating (called stringers) or wooden planks. See Figure 1.

Assembly can be by light construction equipment or by manpower as long as the maximum weight of any one component is about 600 lb. The entire bridge is assembled on a site next to and in line with the desired position of the crossing. A cantilever launching nose, also of standard components, is added to the leading edge. Since the entire bridge is assembled on a set of rollers, the positioning of the structure on the desired site is achieved by simply pushing the bridge across the span. See Figure 2.

Further information on the Bailey bridge can be had from Bailey Bridges, Inc., 201 Woodbridge Street, San Luis Obispo, California, 93401.

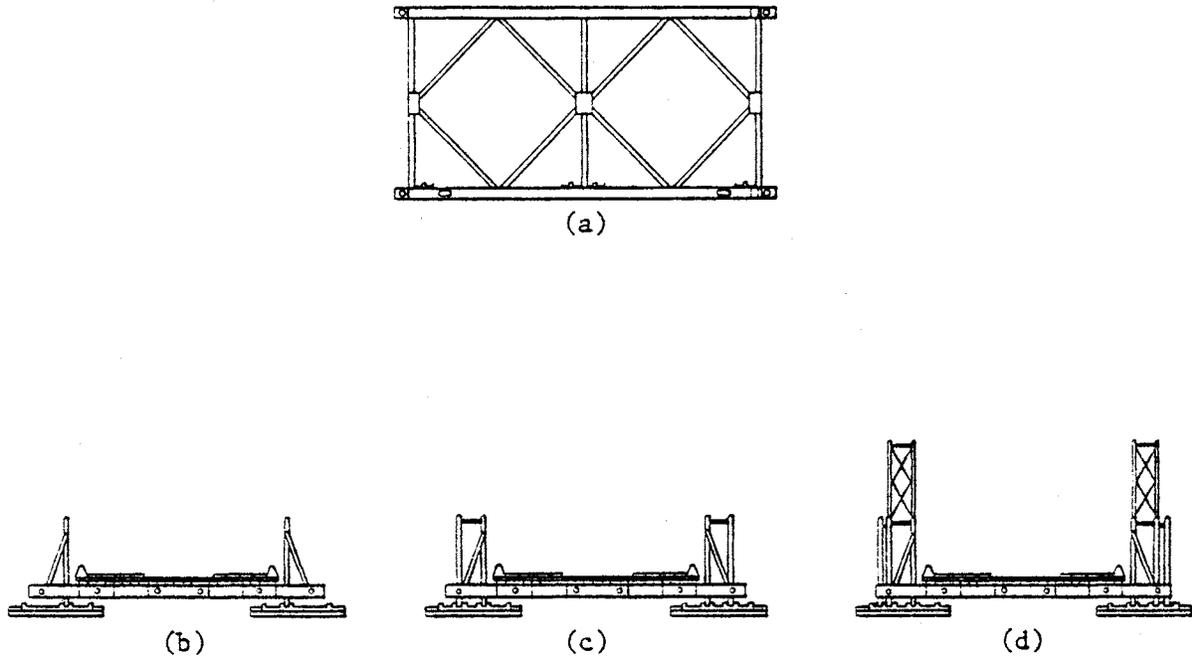


Figure 1

Typical arrangements of truss units

- (a) Basic truss panel
- (b) Cross section using single panels
- (c) Cross section using double panels
- (d) Cross section using triple panels joined with double panels on top

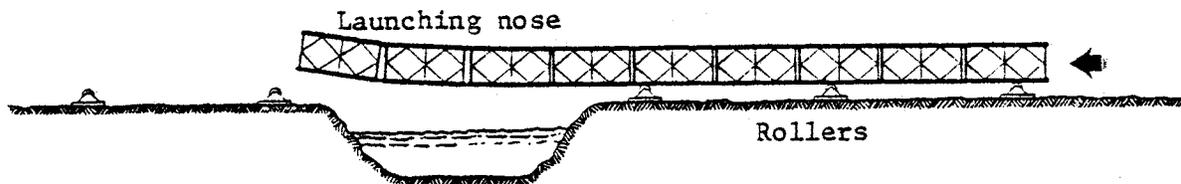


Figure 2

Launching of Bailey Bridge

### Acrow Bridge

The Acrow bridge is an improved and updated version of the Bailey bridge. Modifications were developed by the English engineering firm of Thomas Storey, Ltd. The bridge configuration is essentially the same as that of the Bailey bridge but it is approximately 20% stronger, spanning up to 200 ft. for an HS20 loading. Assembly and launching procedures are similar to those of the Bailey bridge. Intermediate piers, if needed, can also be made of modular Acrow panels.

Although the bridge is generally a single-lane structure, extra wide transoms (transverse floor beams) up to 30 ft. 6 in. long can be had to make the structure double-laned. The prefabricated deck can be of wood planks, open steel grating, or solid steel plating. Some typical details are shown in Figure 3.

For spans up to 300 ft. the Acrow Corporation manufactures a prefabricated modular, through truss steel bridge of a Warren truss configuration called the Acrow Heavy Bridge. It is launched using Acrow panels for the launching nose. See Figure 4.

In addition to these bridges, Acrow makes several other kinds of specialized bridges constructed largely from their standard panels. One special type is a floating bridge in which the pontoons are of hollow steel shells and the trusses spanning between pontoons are of their standard units. Another special bridge is a lift bridge in which the towers and lift span are made from their standard panels. The lifting machinery, however, is custom-made.

Additional detailed information on the Acrow bridges and their costs can be had by contacting the Acrow Corporation of America, 396 Washington Avenue, Carlstadt, New Jersey, 07072.

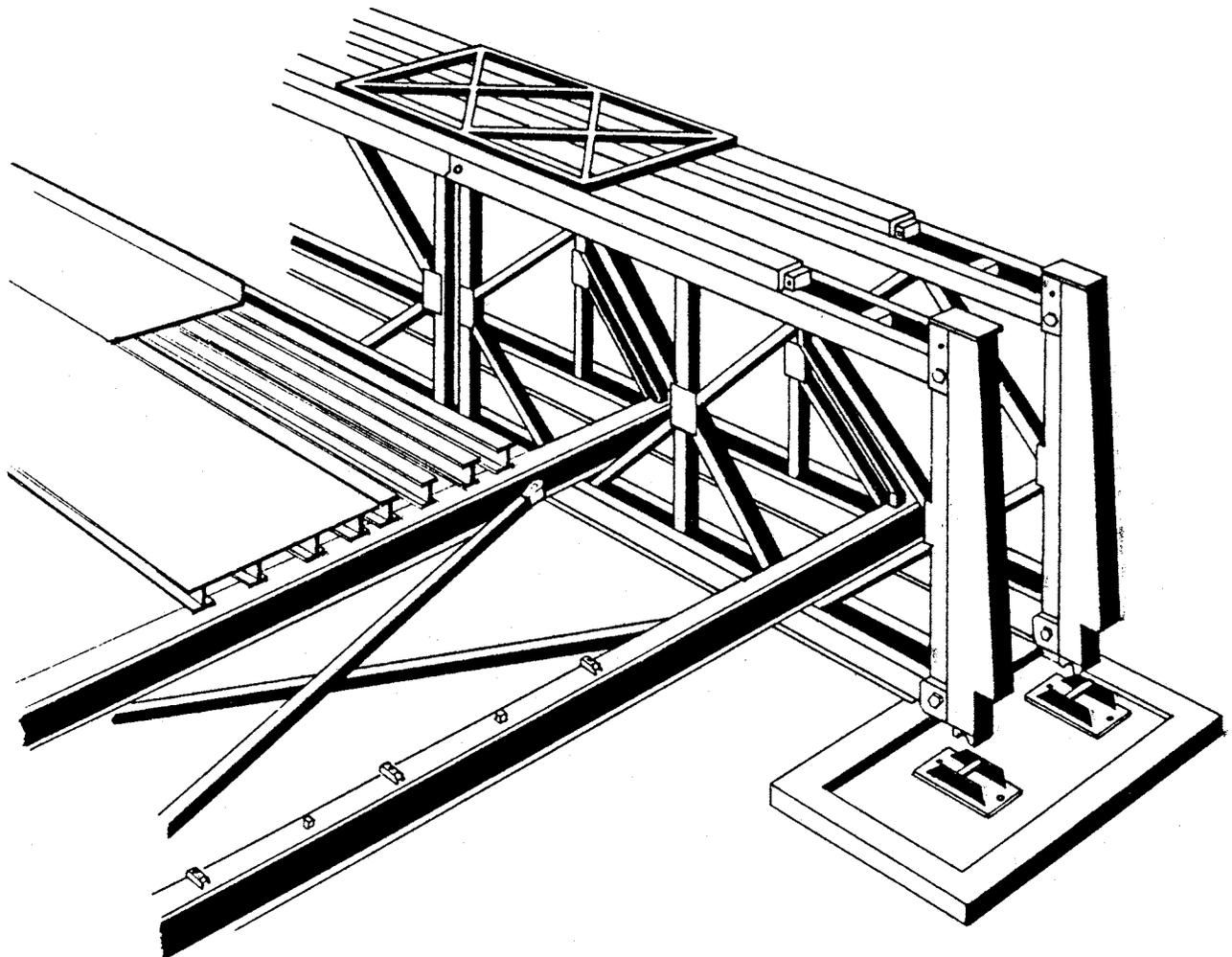


Figure 3

Details of a double trussed Acrow Bridge

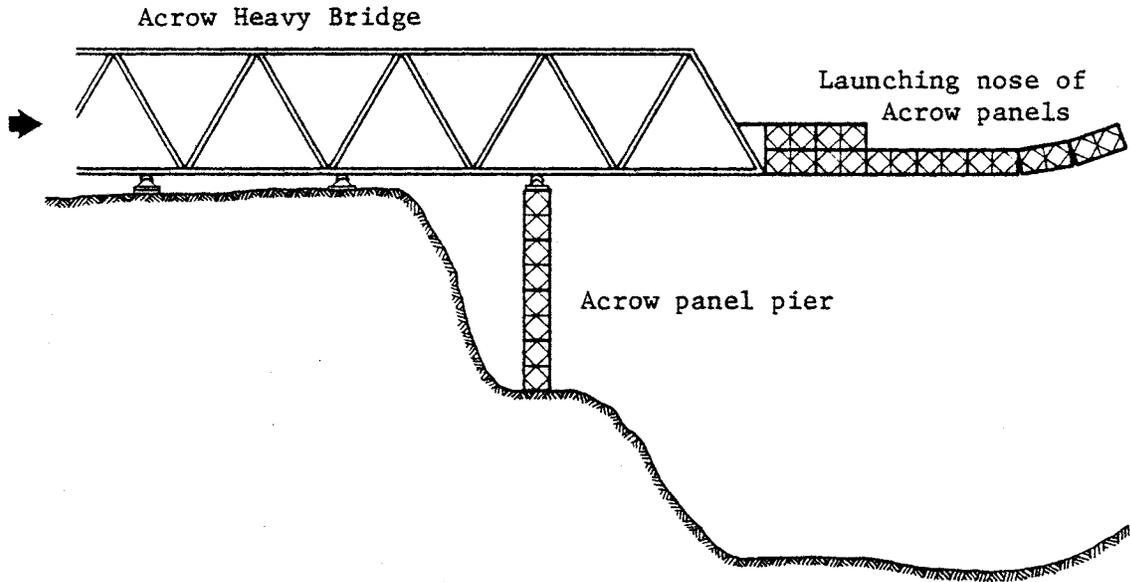


Figure 4

Launching of an Acrow Heavy Bridge

### Medium Girder Bridge

The medium girder bridge was developed by the British to replace the Bailey bridge for military applications. It is also in use by the United States Army.

The basic components of this bridge are 6 ft. long structural units made of aluminum alloy that can be joined together to achieve a variety of spans and strengths. The major units are box beams approximately 21 in. deep and weighing 385 lb. and triangular truss units or sway braces approximately 3 ft. deep and weighing 36 lb. Deck panels approximately 9 ft. wide and weighing 163 lb. connect with the box beams on each side.

For short spans, the box beams alone (without the triangular units) can be pinned together to form a bridge. At a 72-ft. span the structure can support a 16-ton vehicle. By adding the truss units below the box beams, the span can be increased to 160 ft., at which distance it can still support a 16-ton vehicle. At a 100-ft. span it can support a 60-ton vehicle.

A third strengthening modification is also possible. With cables added below the trussed box girder in a queen post configuration, the 160-ft. span is able to support a 60-ton vehicle. Special tapered end units are added to facilitate ramping onto the bridge. See Figure 5.

Launching of the bridge is with the aid of a temporary launching nose made of box beam units attached to one end. Only one such nose beam is needed; it is positioned midway between the bridge box beams. As with the Bailey bridge, assembly is done on rollers in line with the bridge site. The bridge is then pushed across the span. See Figure 6.

Although the basic bridge is only one lane wide, the structure is of a deck type that permits several such bridges to be placed side by side to produce a multiple-lane roadway. Should a span exceed 160 ft., one or more intermediate pier supports can be placed to bridge any desired overall distance. Prefabricated and adjustable metal piers with their own footings are available for this purpose.

Detailed information on this bridge, much of which is unclassified, may be obtained from the U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia, 22060.

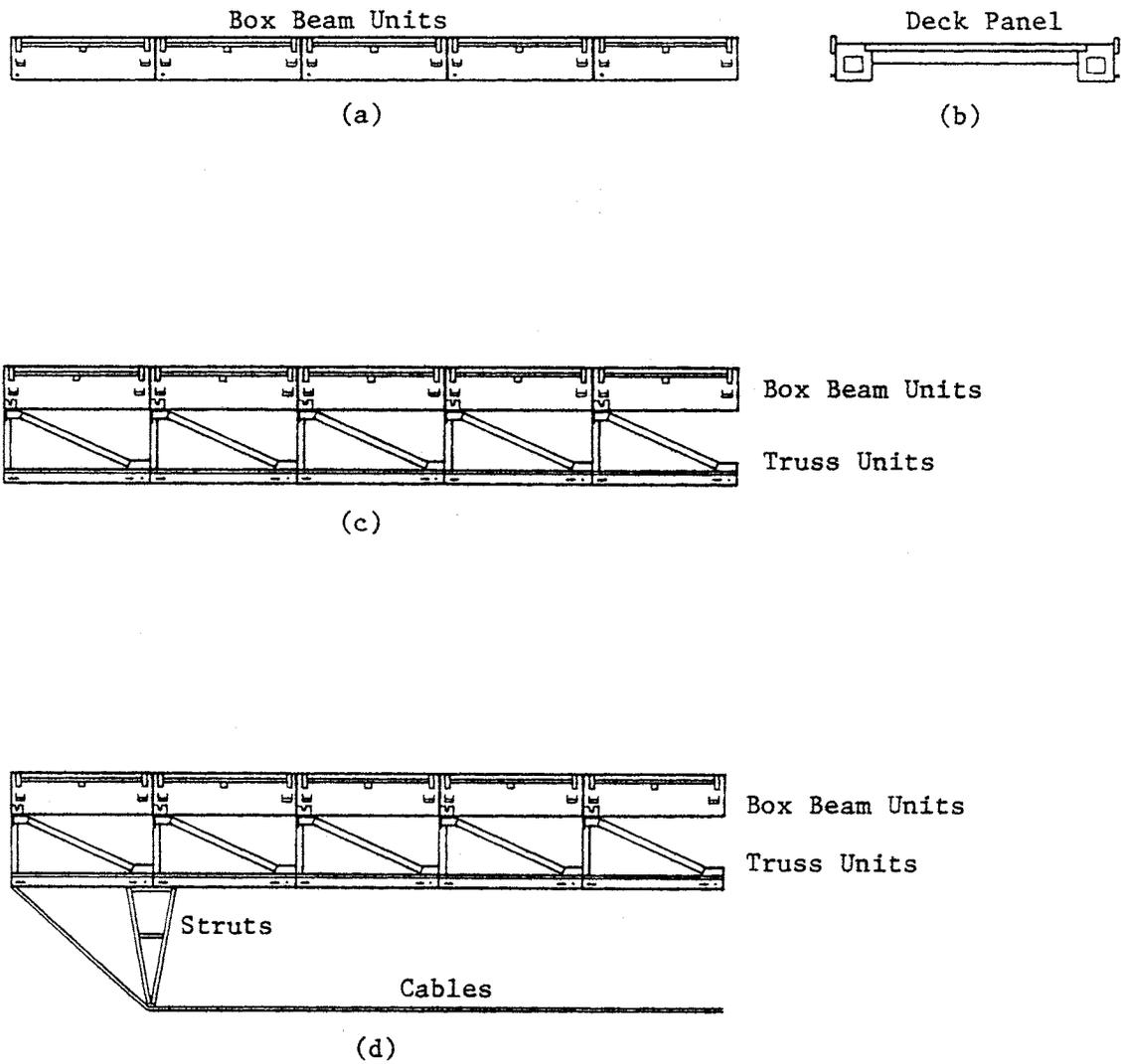


Figure 5

Basic structural configurations

- (a) Joined box beam units
- (b) Cross section of bridge with box beam units
- (c) Joined box beam and truss units
- (d) Joined box beam and truss units with cable reinforcing

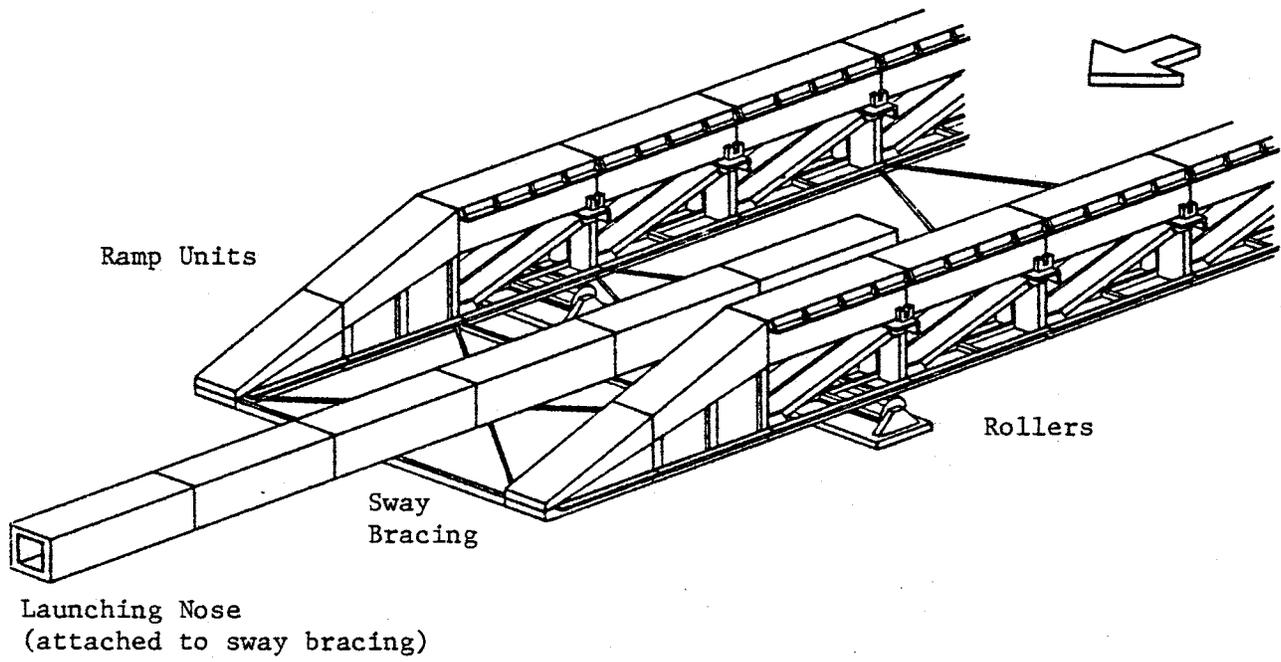


Figure 6

Launching of Medium Girder Bridge

### Rheinhausen Fast Assembly Bridge

Built by Krupp in West Germany, the Rheinhausen bridge system is a prefabricated steel structure that can be dismantled and reused. The basic structure is a unitized panel consisting of girders, floor beams, and steel deck components, and either 8 or 12 m in length and approximately 3 m wide and 1 m deep. See Figures 7 and 8.

For long bridges, intermediate supports are needed at intervals of 8 or 12 m. The panel units can be joined to form bridges in any width in multiples of 3 m. All components are joined with bolts. Normally, the main panels are welded to form a single unit; but where transport is a problem, the girders, floor beams, and deck plates can be shipped separately and bolted together at the site.

The fast assembly bridge can be furnished complete with paint, drainage pipes, sidewalks, curbs, guardrails, skid resistant surfacing, and brackets for lighting masts as desired.

This bridge system has been used in several countries including Germany, Holland, Spain, and Venezuela. The longest one is a 728-m viaduct in Hannover, W. Germany, built to relieve a congested traffic situation until permanent facilities can be constructed.

Further information on the Rheinhausen bridge can be obtained from the Krupp Company, Rheinhausen, W. Germany.

### Nobels-Kline Bridge

Conceived in Belgium by the firm of Nobels Peelman, this bridge system has been developed and manufactured in association with the American firm of Kline Iron and Steel.

The basic bridge components are weathering steel, tee-shaped girders in which an orthotropic deck section 6 ft. wide is welded to a stiffened web. A narrow lower flange is attached to the bottom of the web. The total depth of the section is 3 ft.-6in. The girders can span up to 80 ft. as simply supported beams and support an HS20 load.

The 80 ft. long girders can also be used for spans as short as 50 ft., with 15 ft. cantilevers. Spans as long as 110 ft. can also be had by joining 15-ft. cantilever segments with the standard 80-ft. girder. Erection is by means of mobile cranes.

All field connections are bolted, so that the superstructure of the bridge is fully relocatable. Piers may or may not be reusable, depending on their design, which is related to the specific site.

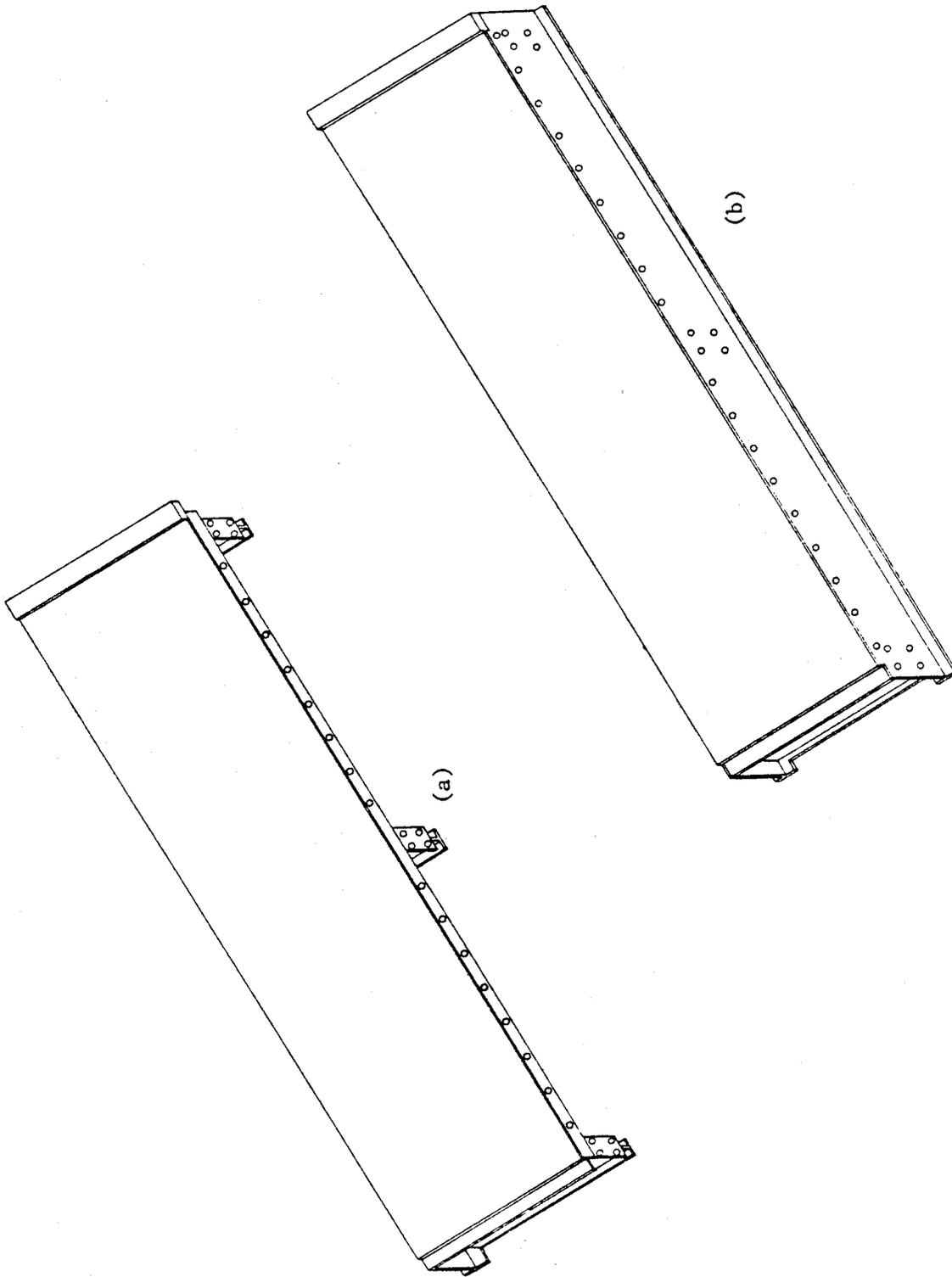


Figure 7  
Unitized superstructure panels  
(a) Unit with single stringer  
(b) Unit with double stringer

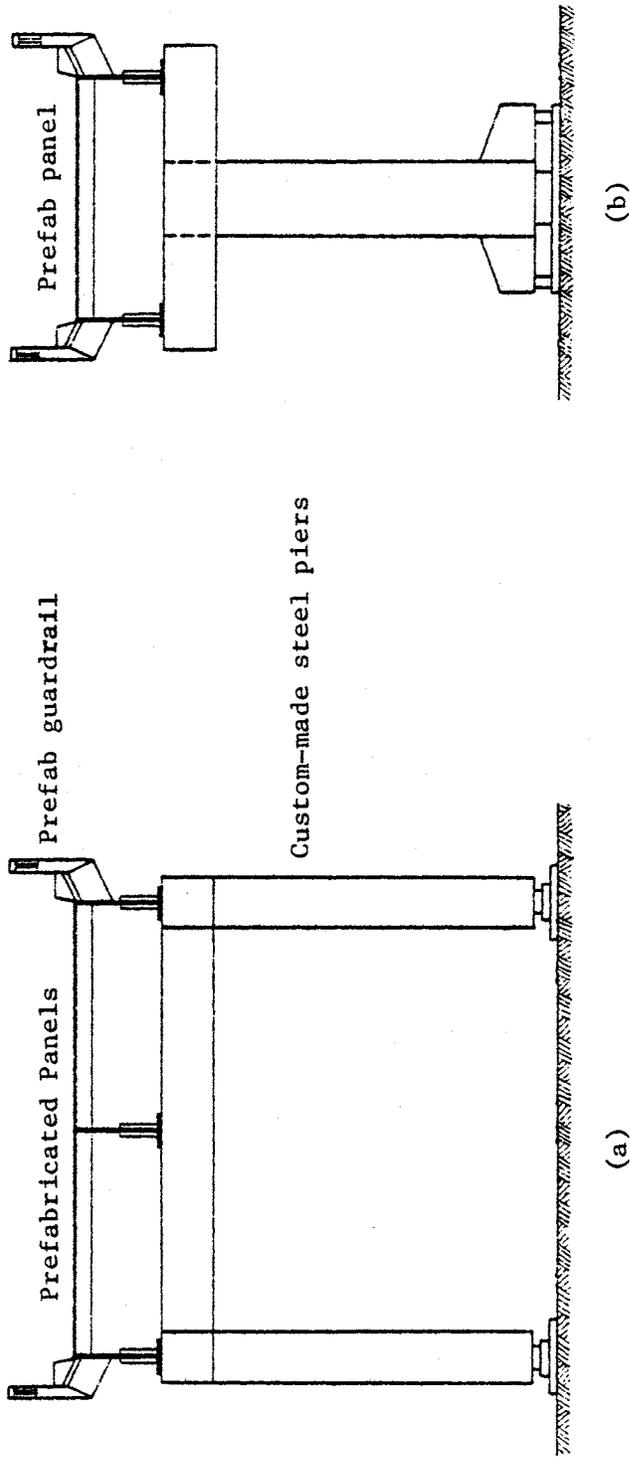


Figure 8  
 Typical bridge cross sections  
 (a) Double-lane bridge  
 (b) Single-lane bridge

The deck surface has a factory applied coating of quartz filled epoxy resin so that no additional wearing surface need be applied in the field.

Bridges of any width in multiples of 6 ft. can be made by joining the prefabricated girders. See Figure 9.

Standard supplementary components as steel parapets, sidewalks, curbs, and light poles are available to attach to the standard girders. Special trapezoidal or curved girders can be had to fit with the standard straight rectangular girders for curved roadways.

Recent installations, mainly as viaducts, of the Nobels-Kline bridge have been made in a number of cities as Antwerp, Brussels, Caracas, Cairo, and Teheran. Further information on this bridge system may be had from Nobels-Kline, Ltd., P.O. Box 1013, Columbia, South Carolina 29202.

#### Nobels-Kline Emergency Bridge

Made by the same firm that manufactures the orthotropic steel bridge previously described, this emergency bridge is a one-lane truss structure. Basically a Warren truss of weathering steel, it is made of standard components capable of spanning from 12 to 68 m in 4 m increments. The basic truss depth is 3.5 m. Depending on the span and loading, either HS15 or HS20, various combinations of truss components can be assembled, much as for the Bailey and Acrow bridges. See Figure 10.

The bridge is assembled with high strength bolts and can be erected either by crane or by launching with a launching nose built of standard elements. The prefabricated steel deck comes complete with a skid resistant epoxy layer. Sidewalks can be added if needed.

For further information, contact Nobels-Kline, Ltd., P.O. Box 1013, Columbia, South Carolina 29202.

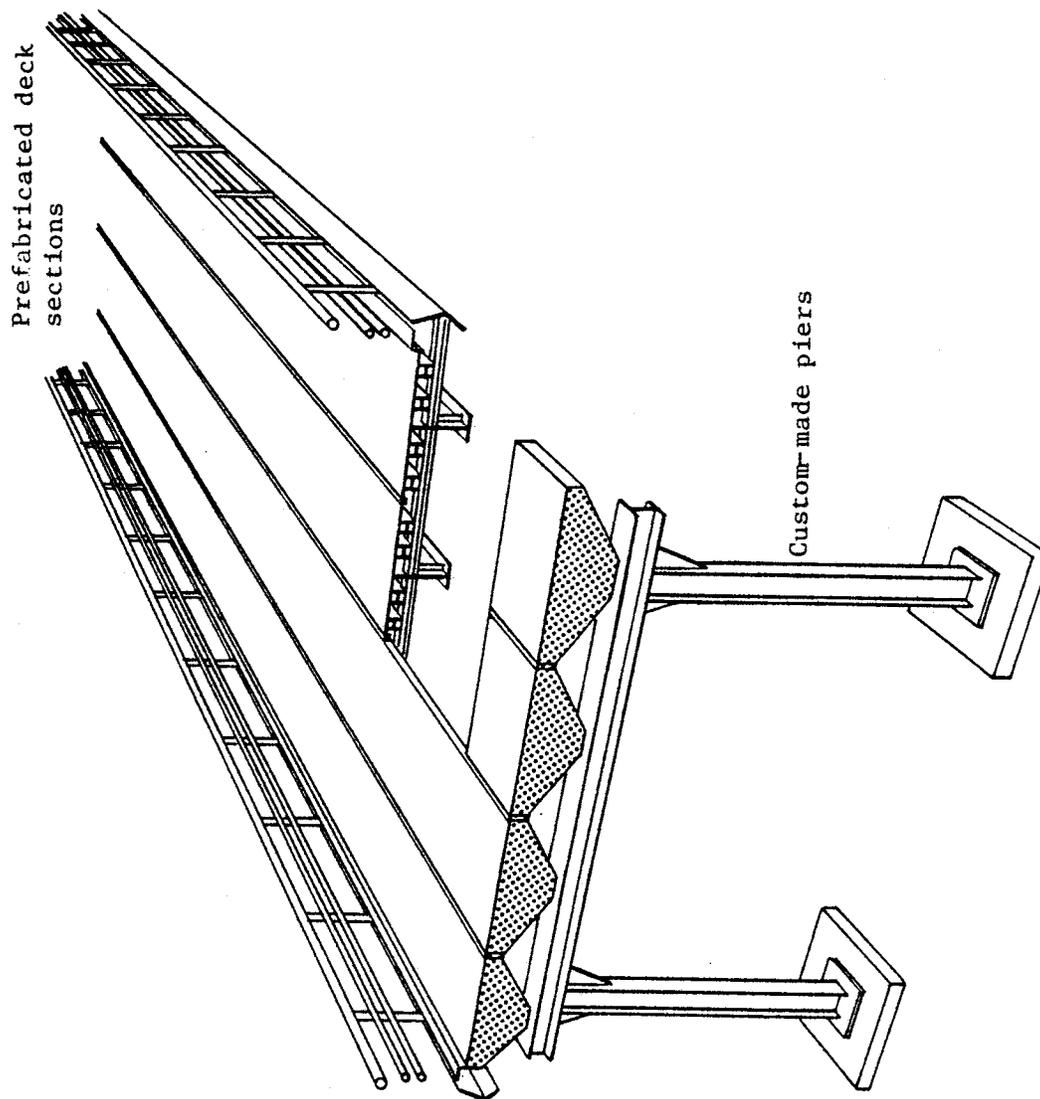


Figure 9  
Nobels-Kline Bridge

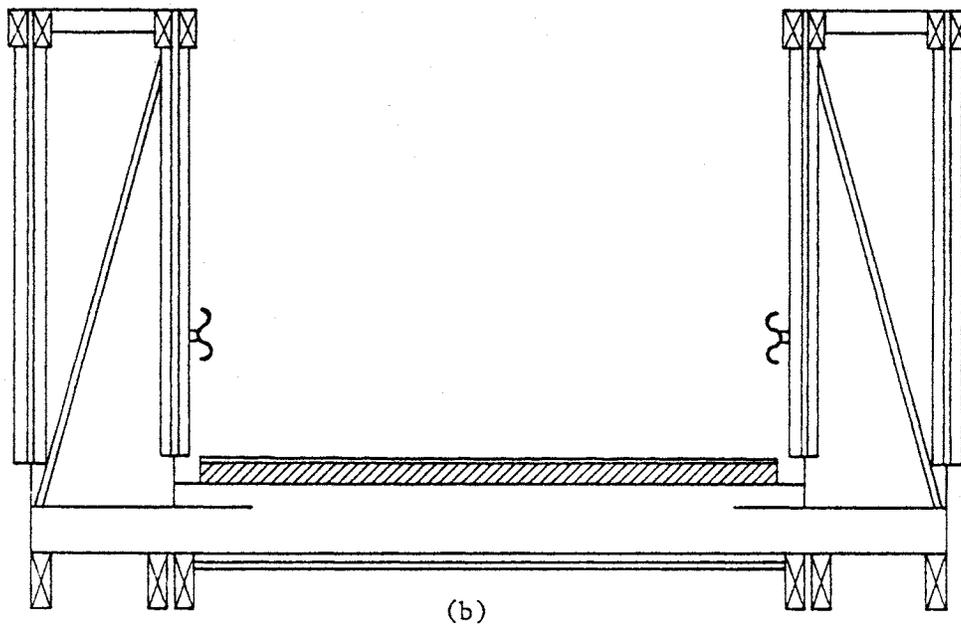
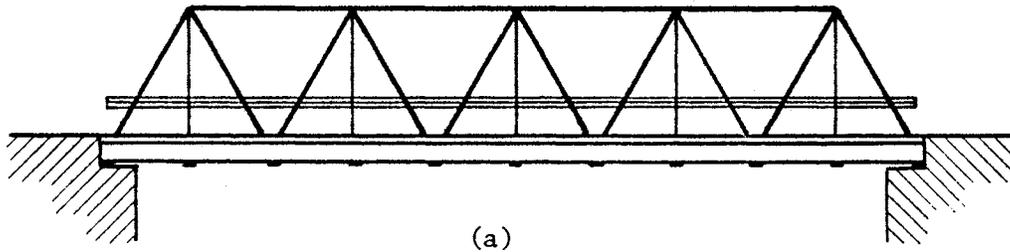


Figure 10

Nobels-Kline Emergency Bridge  
(a) Typical assembled bridge  
(b) Cross section of bridge with double trusses

### Demountable Concrete Bridge

Although most relocatable bridge systems are of metal, one system, developed by the firm of Dyckerhoff and Widmann in West Germany, is of concrete. A major application of the system was for a temporary viaduct 190 m long in Munich.

The main superstructure is made of only three types of precast, prestressed hollow box beams. Type 1 is 20 m long, is made of dense concrete, and weighs 20 tons. Type 2 is 30 m, is made of lightweight concrete, and weighs 30 tons; it is designed so that the 5 m on each end function as a cantilever. Type 3 is 30 m long, is made of lightweight concrete and weighs 30 tons. Each beam is 750 mm wide and 900 mm deep with a single circular void 500 mm in diameter running its length. The beams are formed with stepped ends which provide the bearings. Using these three types, it is possible to form clear spans ranging from 20 to 40 m in increments of 5 m. See Figure 11.

Supported by precast concrete piers, the box beams are placed adjacent to one another to form a deck of almost any desired width. See Figure 12.

The box beams are secured transversely by epoxy coated post-tensioning rods, using threaded nut end restraints so that non-destructive dismantling is possible.

Provision is made for the attachment of precast parapets and other miscellaneous features. A wearing course of bituminous material up to 160 mm can be applied without overloading the bridge and can be removed for dismantling.

For further information on the system, contact Dyckerhoff and Widmann, Inc., 529 Fifth Avenue, New York, NY 10017.

### Ribbon Float Bridge

Patterned after a successful design of the U.S.S.R., the ribbon bridge is an American version developed by the U.S. Army for use as a pontoon bridge in temporary crossings of wide bodies of water. The Russian bridge is made of steel, whereas the American bridge is made of aluminum and is much lighter.

The basic float unit, weighing approximately 11,100 lb., is transported in a folded configuration 22.5 ft. long, 10.7 ft. wide, and 7.7 ft. high. When unfolded for use, each unit is 22.0 ft. long, 26.5 ft. wide, and 3.5 ft. deep. The effective roadway width is 13.5 ft. The bridge is designed to support a 60-ton vehicle load.

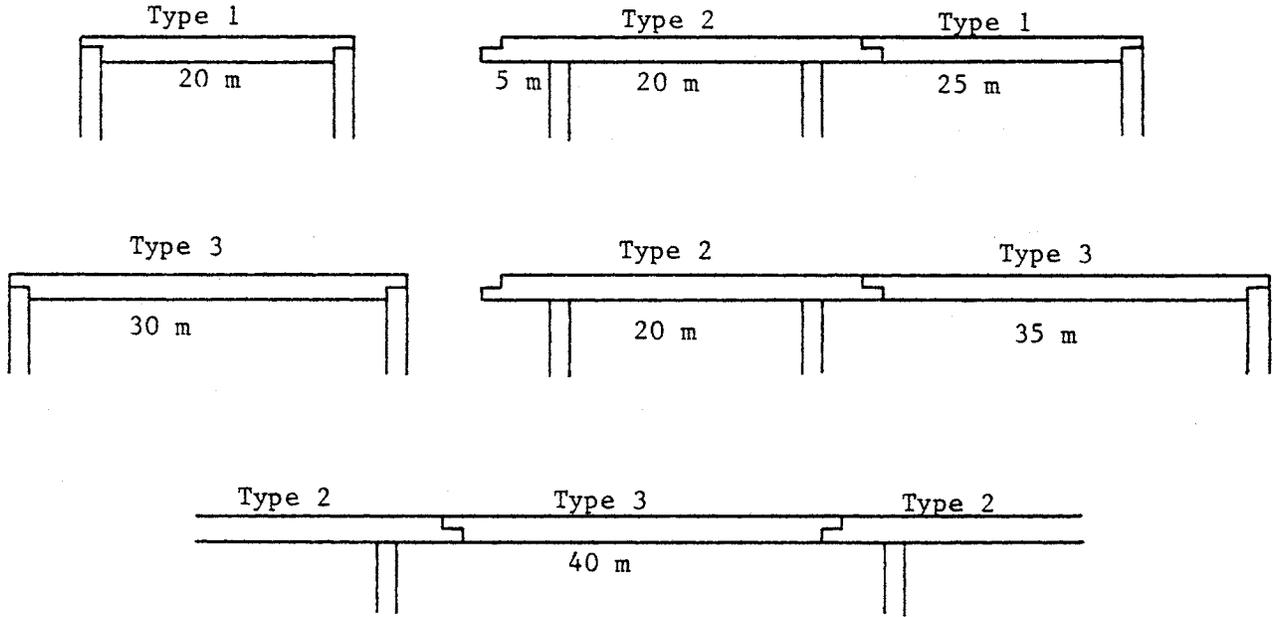


Figure 11

Arrangements of beams for spans 20, 25, 30, 35 and 40 meters

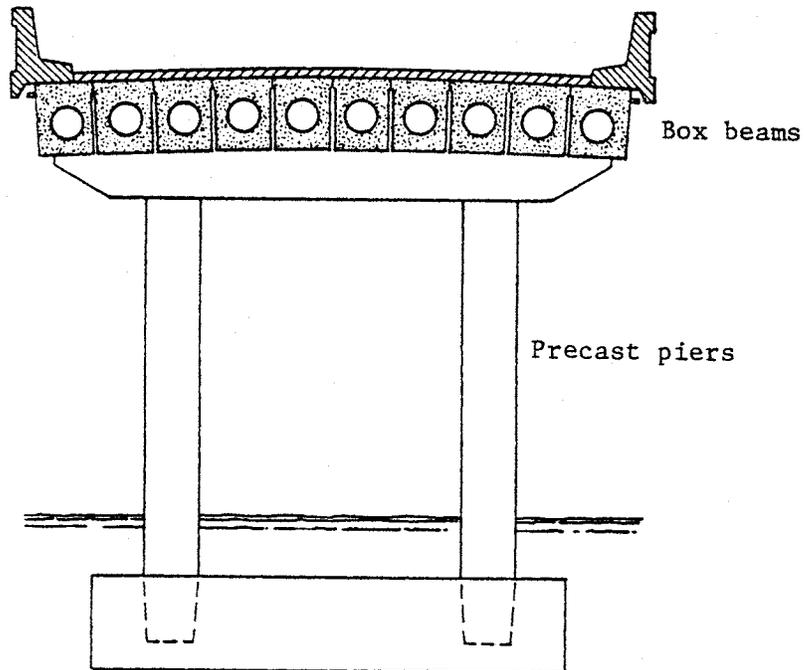


Figure 12

Typical cross section of concrete bridge

Construction of the floating bridge is as follows. The truck carrying a unit is backed into the water, allowing the unit to slide off into the water. There, the unit is unfolded and joined by pins to its mating unit. Assembly is usually done along the shore edge. When the bridge is assembled full length, it is swung across the water span by boats and then anchored to shore by cables. Retrieval is done in a reverse manner, with the unit pulled on to the transport vehicle by a truck mounted winch. See Figure 13.

Special end pontoons are provided to facilitate ramping onto the bridge. Simple railings can also be attached.

For further information on unclassified aspects of this floating bridge, contact the U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia 22060.

#### Martin Marietta Expandable Bridge

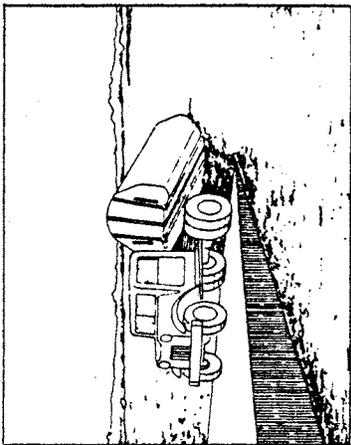
An experimental, lightweight, expandable bridge has been developed by Merton L. Clevett, Jr., in conjunction with the Martin Marietta Corporation. Made of folding scissor or pantograph beams of aluminum, it can be folded to a small fraction of its length for easy transport by either surface vehicles or helicopters.

See Figure 14 for the construction of a 30 ft. long footbridge, approximately 2 ft. deep and weighing only 110 lb. Note the adjustable cables at the bottom for tensile resistance. The deck, which can be of solid plywood or honeycomb sandwich panels, is designed to resist longitudinal compressive forces in the truss as well as to provide vertical support for pedestrians or light vehicles.

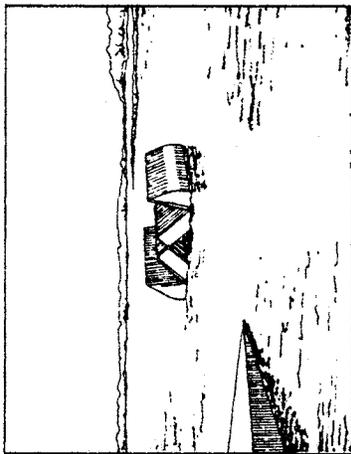
A similar concept is envisioned for a longer and stronger vehicular bridge. See Figure 15.

Although the unfolding of such an expandable bridge can be done quickly and easily, the positioning of the bridge across the span requires the use of special construction equipment as a crane or temporary gin pole. However, the bridge can be adapted to various spans up to its designed length limit and is collapsible for reuse.

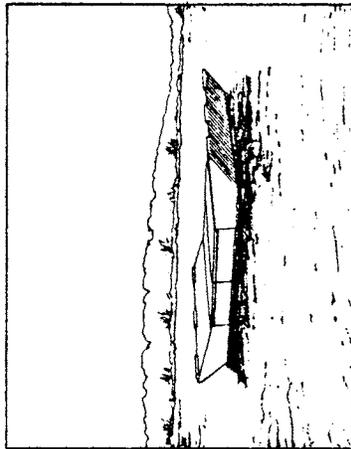
No production bridges are available at this time, but further detailed information on this expandable bridge can be had from Bud Clevett, 4685 S. Ogden Street, Englewood, Colorado 80110.



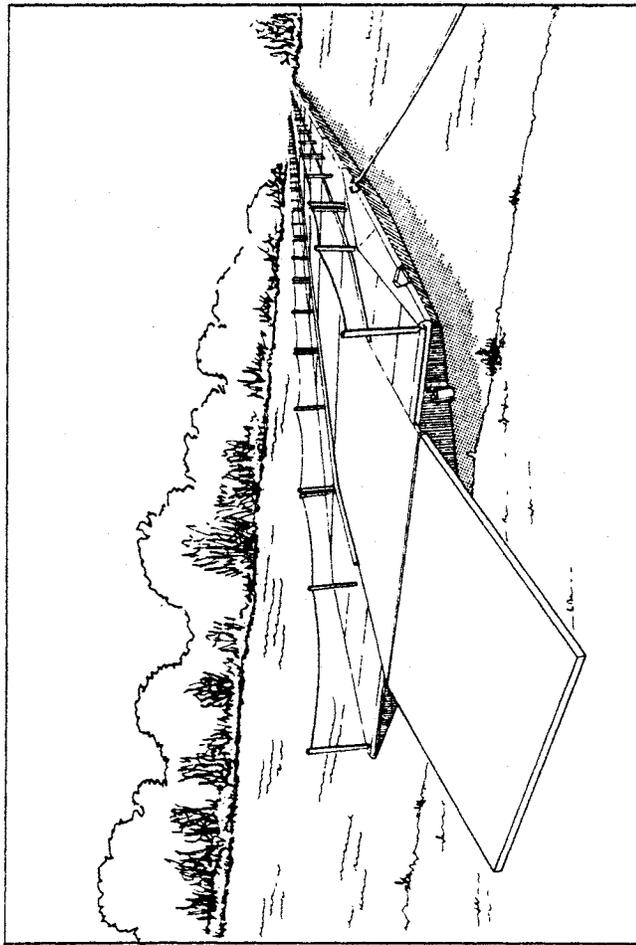
(a)



(b)

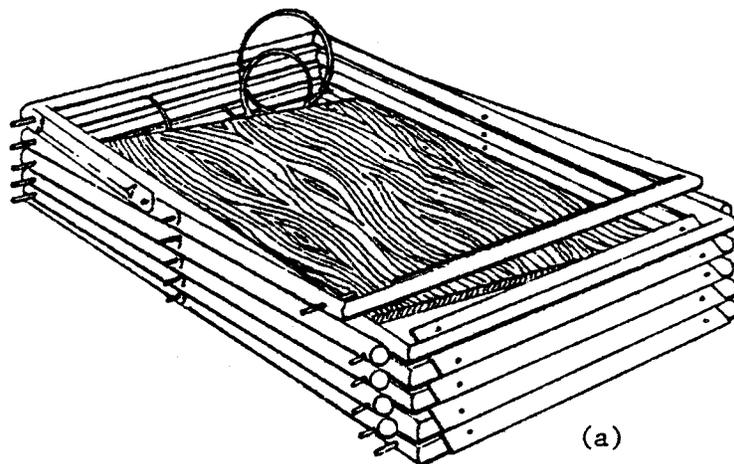


(c)

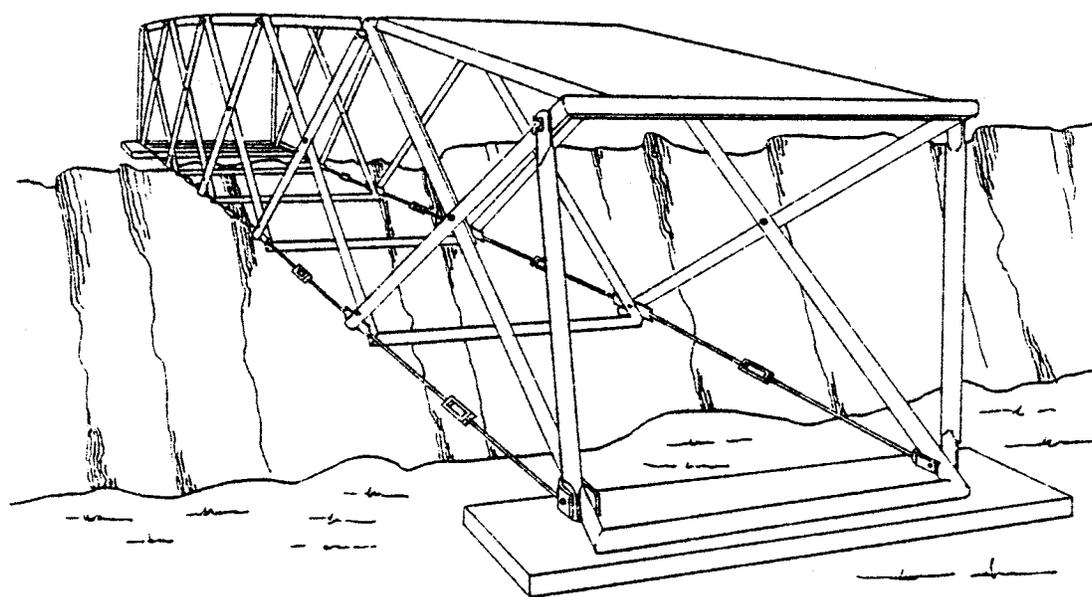


(d)

Figure 13  
Ribbon Float Bridge  
(a) Unloading unit  
(b) Opening unit  
(c) Opened unit  
(d) Completed bridge



(a)



(b)

Figure 14

Expandable Bridge  
(a) Bridge folded  
(b) Bridge deployed

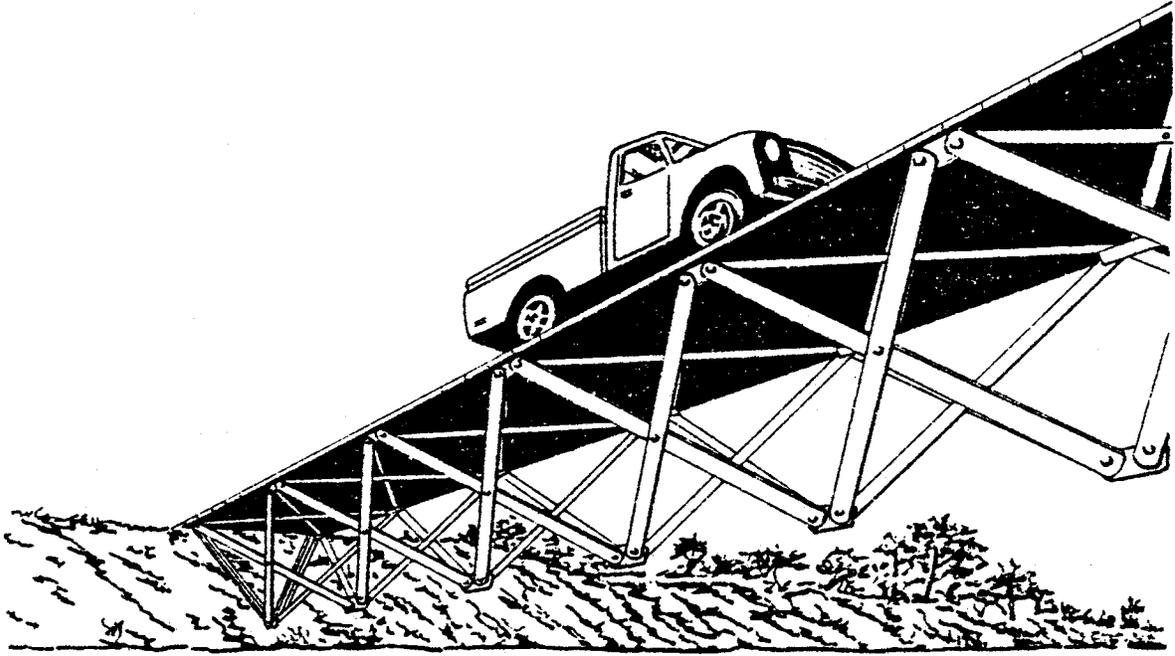


Figure 15

Expandable vehicular bridge

## Folding Bridge

The folding bridge described is a concept developed by the writer which possesses certain properties not found in other relocatable bridges. See Figure 16. The concept presumes the development of materials and hardware of adequate strength and durability necessary for practical use. It is envisioned that the web members and deck plates are metal faced sandwich panels and the lower chords are flat metal plates. Simple metal hinges join all folding elements. The hinges at the ends of the structure would also incorporate bridge bearing hardware.

For storage and transport, the web and lower chord would be folded in one bundle and the deck plates, also folded, would be in a separate bundle, as seen in Figure 17. Modular deck, web, and lower chord units could be added or subtracted to accommodate the desired unfolded span length.

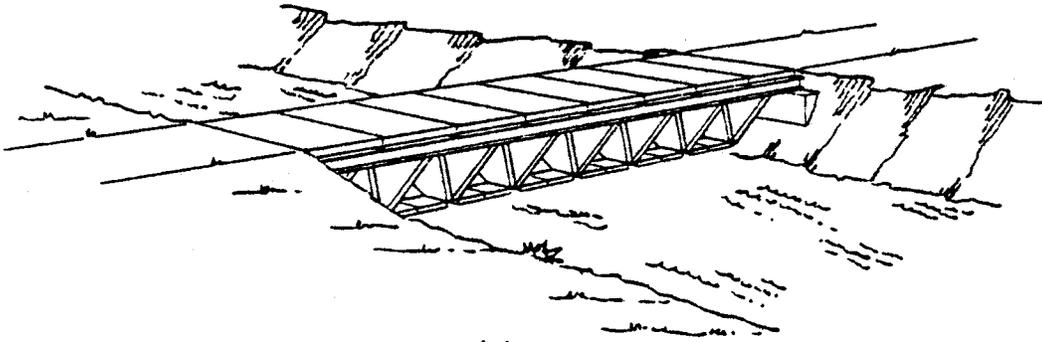
For erection, two precut metal edge beams would be placed across the span on suitable supports; one on each side of the bridge position. The folded web-chord bundle would then be placed on the edge beams at one side of the span. Lugs attached to the top edges of the web members support the bundle. The lugs would then be pushed or pulled along the edge beams to unfold the webs and lower chords.

At this stage, the folded deck plates are placed on the edge beams at one end of the span and then pushed or pulled to unfold. Bolts are placed to attach the deck plates to the top edges of the web members. The basic erection process is illustrated in Figure 18. Finally, railings and other fixtures can be attached to the deck. The final result is an attractive structure, constructed from only two basic assemblages.

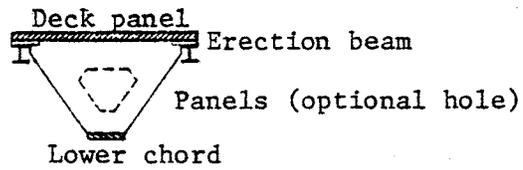
Dismantling may be carried out in reverse of the erection process, with the units then being ready for storage.

## M60 Armored Vehicle Launch Bridge (AVLB)

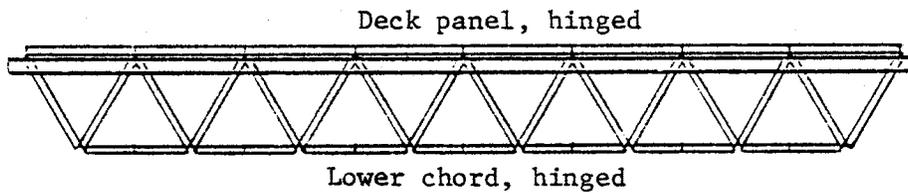
A highly sophisticated single-lane, short-span bridge has been developed by the U.S. Army for spans up to 63 ft. This self-launching bridge of aluminum is transported on the back of a special launch vehicle with tank treads and can be deployed hydraulically in a matter of minutes by an operator remaining within the vehicle. Its primary use is for the emplacement of a bridge under conditions of military assault or enemy fire. See Figure 19. The Warsaw Pact armies also have a similar type of scissor bridge (MT-55) capable of spanning about 60 ft. and carrying a 50-ton vehicle.



(a)



(b)



(c)

Figure 16

Basic bridge

(a) Erected bridge

(b) Cross section of bridge (railings not shown)

(c) Elevation of bridge

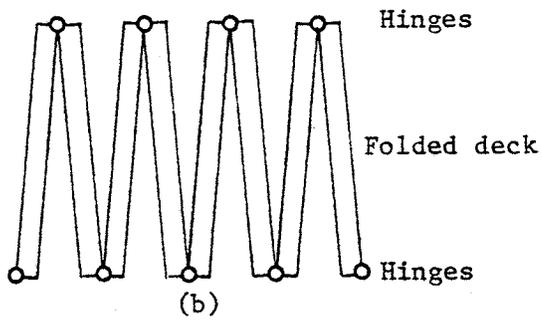
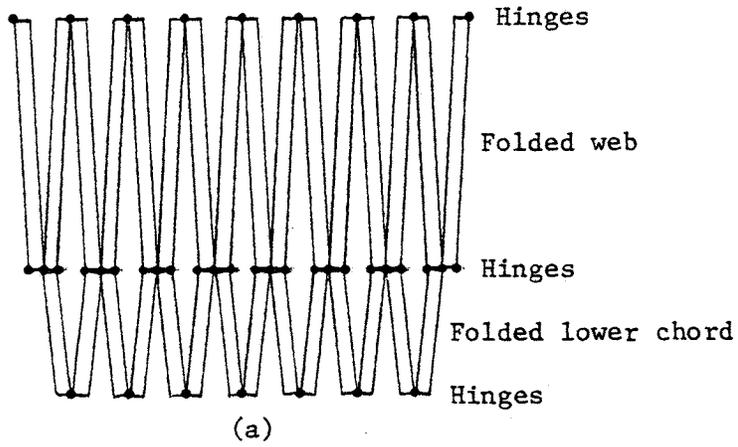


Figure 17

Folded bridge components  
 (a) Web and lower chord  
 (b) Deck

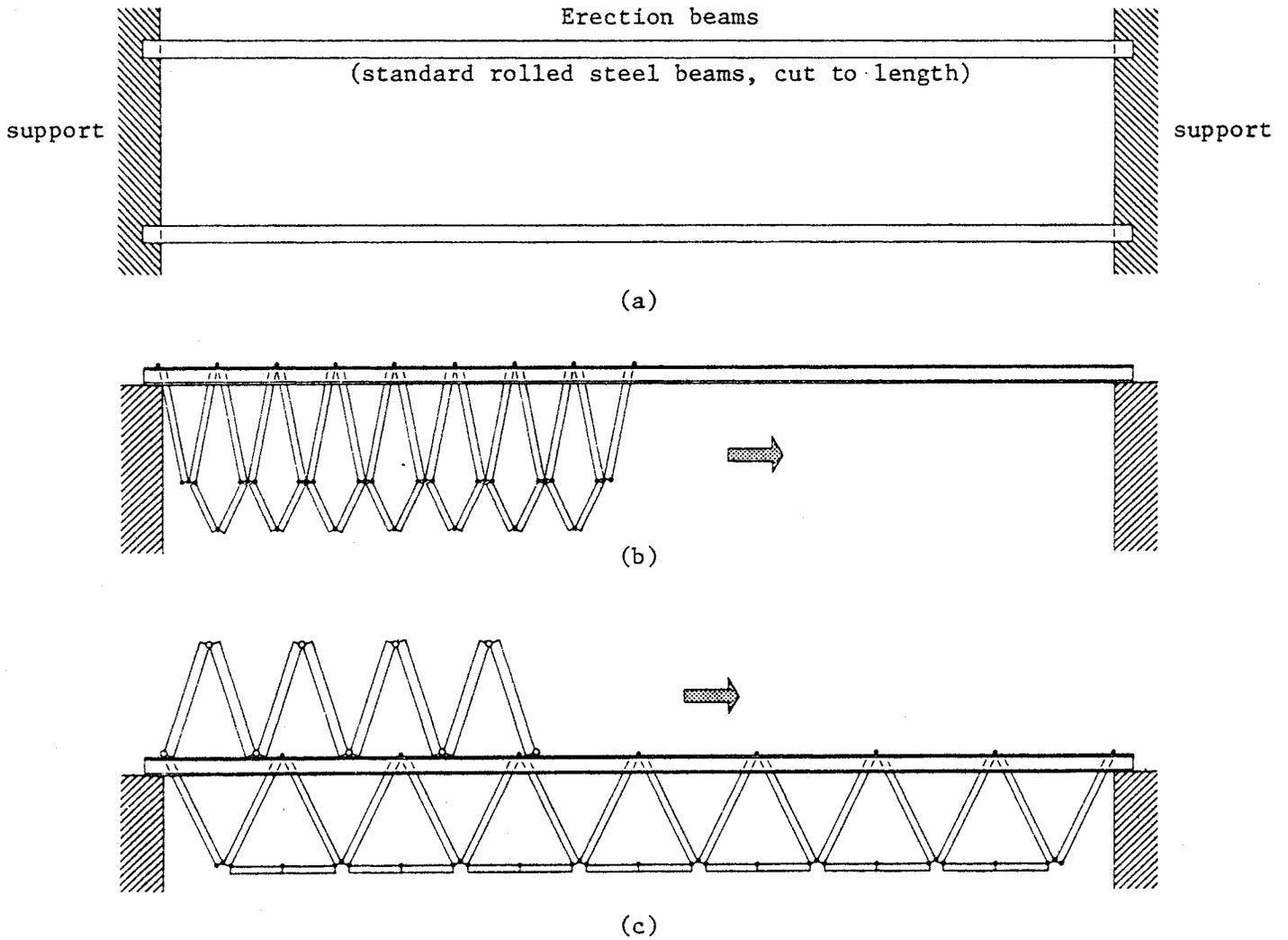
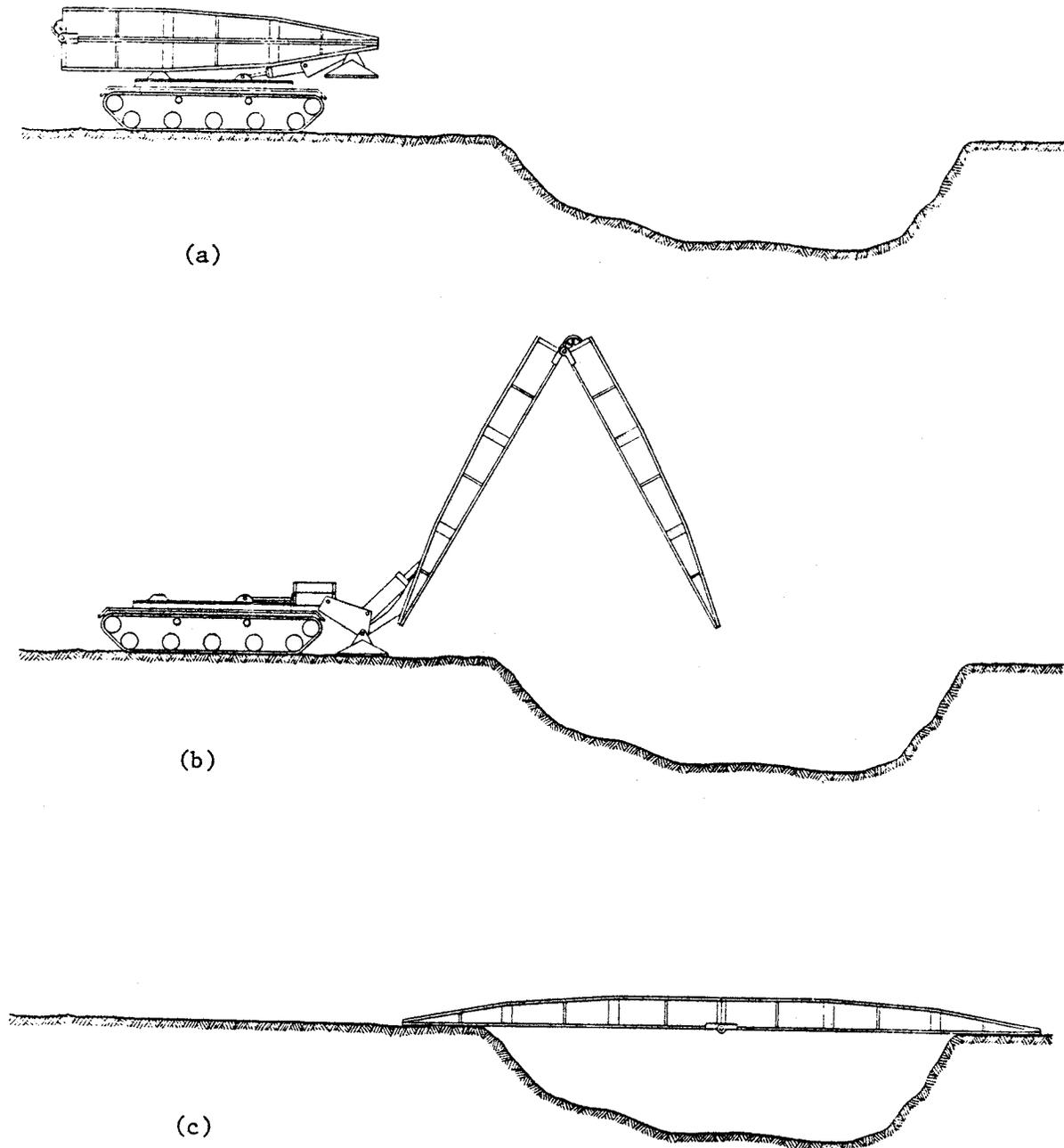


Figure 18

Erection sequence

- (a) Plan view of erection beam placement
- (b) Elevation view of web and lower chord being pulled into place across erection beams
- (c) Elevation view of deck being pulled into place across erection beams



(a)

(b)

(c)

Figure 19

Armored vehicle launch bridge

(a) Folded for transport

(b) Deployment

(c) In place (bridge may be retracted from either end)

Although an excellent piece of engineering, this type of bridge has little direct application for civilian purposes and is expensive to produce. However, further nonclassified information may be obtained from the Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia 22060.

The Warsaw Pact countries, as Russia, Poland and Czechoslovakia, have further refined their scissor bridges to include an integral telescoping trestle for support in shallow water. By launching multiple scissor bridges with integral piers, total bridge lengths can be extended almost indefinitely. Several countries in Western Europe are working on similar integral pier concepts. For further details, refer to the Dec. 1979 issue of the Military Engineer magazine.

### Bridge of the Eighties

A tactical support bridge being developed by the U.S. Army is a versatile, rapidly deployable bridge capable of spanning either 30 or 50 m and supporting a 60-ton vehicle load. Essentially, it is a one-lane bridge made of two aluminum box girders separated by a gap. Transport is on a special vehicle, either wheeled or tank treaded. In transit, the bridge is carried folded. The basic bridge consists of four sections: two center sections each approximately 7.5 m long and two tapered end sections each approximately 7.5 m long — totalling 30 m. The end sections are folded over the center sections for compactness.

The transport vehicle has a telescoping launch boom located in the gap between the twin girders that is hydraulically extended across the span for erection of the bridge. After the bridge is automatically unfolded to full length, it slides out along the boom for placement. The boom is then retracted. See Figure 20.

The 50-m bridge must be carried on two transporters, where each vehicle carries two interior sections and one tapered end section. The end sections are folded back on the interior sections for transport. See Figure 21.

After the interior sections are joined and the end sections unfolded, the bridge is deployed by a launching boom as in the case of the basic 30 m bridge. For water crossings, floatation covers can be added to interior sections of the 15-m long box girders, so that the girder units can be made into a pontoon bridge. Before launch, the basic box girders are reinforced with an internal king post kit. See Figure 22.

Further unclassified information on this relocatable bridge may be obtained from the U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia 22060.

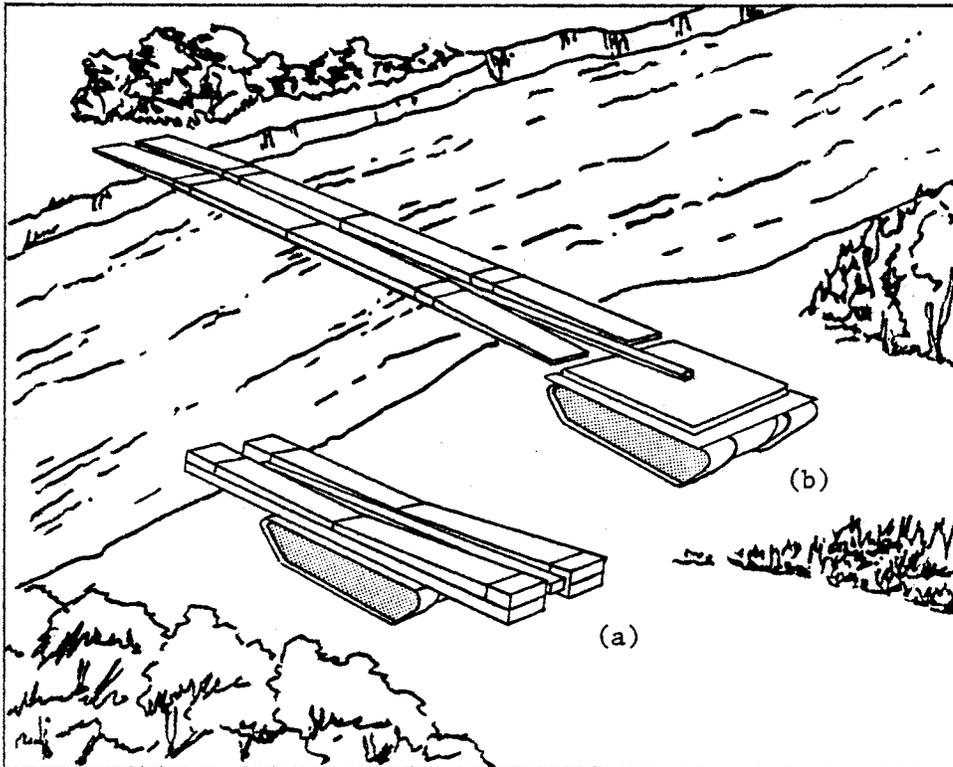


Figure 20

30-meter bridge

(a) Folded for transport

(b) Deployed by launching boom

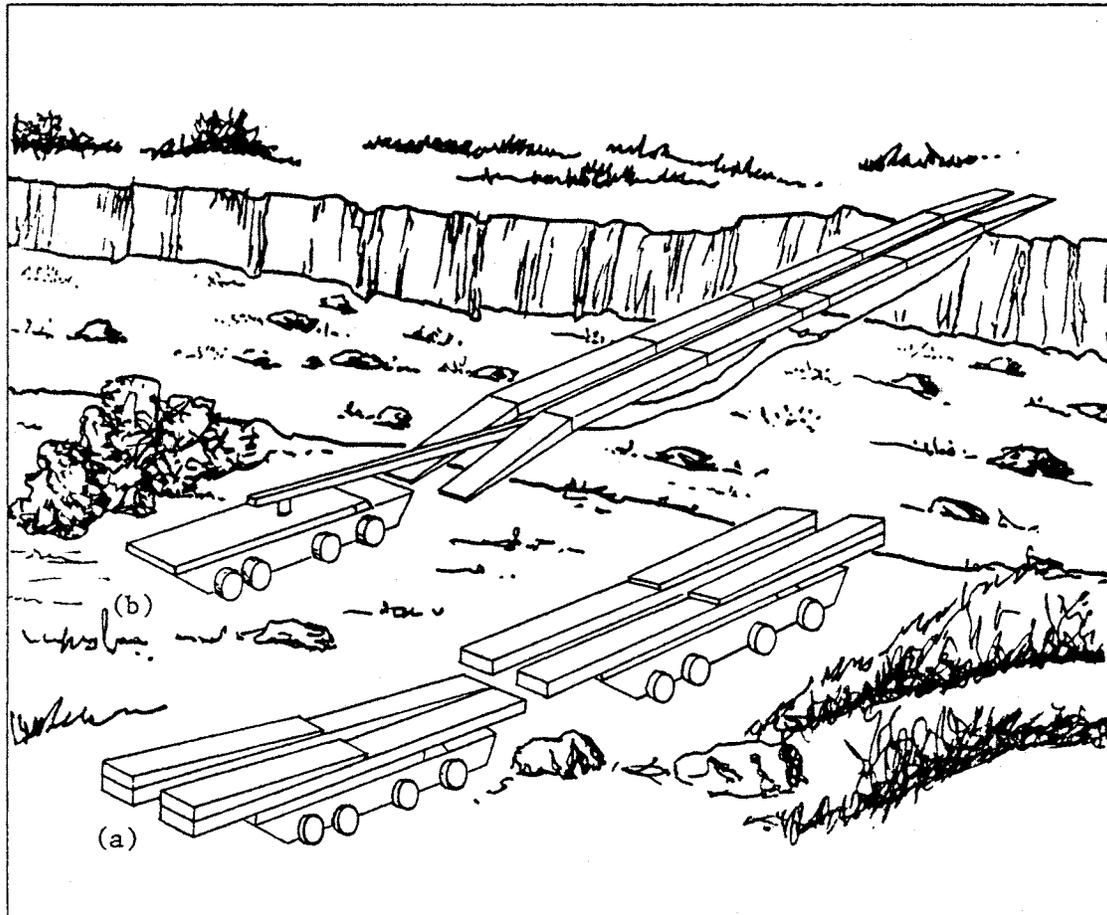


Figure 21

50-meter bridge

(a) Folded for transport

(b) Deployed by launching beam

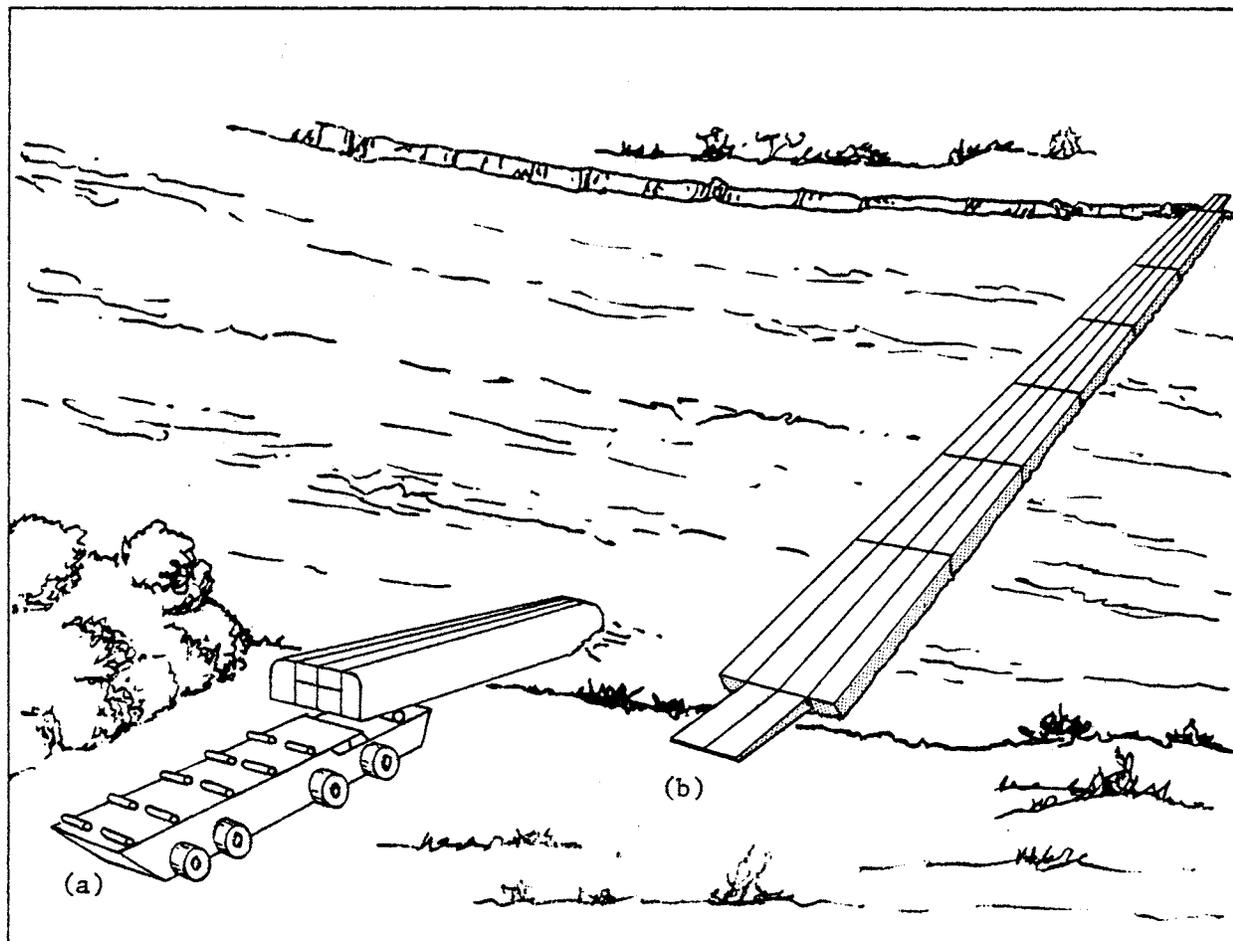


Figure 22

Pontoon bridge

- (a) Launching with floatation covers
- (b) Assembled bridge

### Pneumatic Bridge

Developed in England for military applications is this unusual experimental pneumatic bridge made of rubberized fabric. See Figure 23.

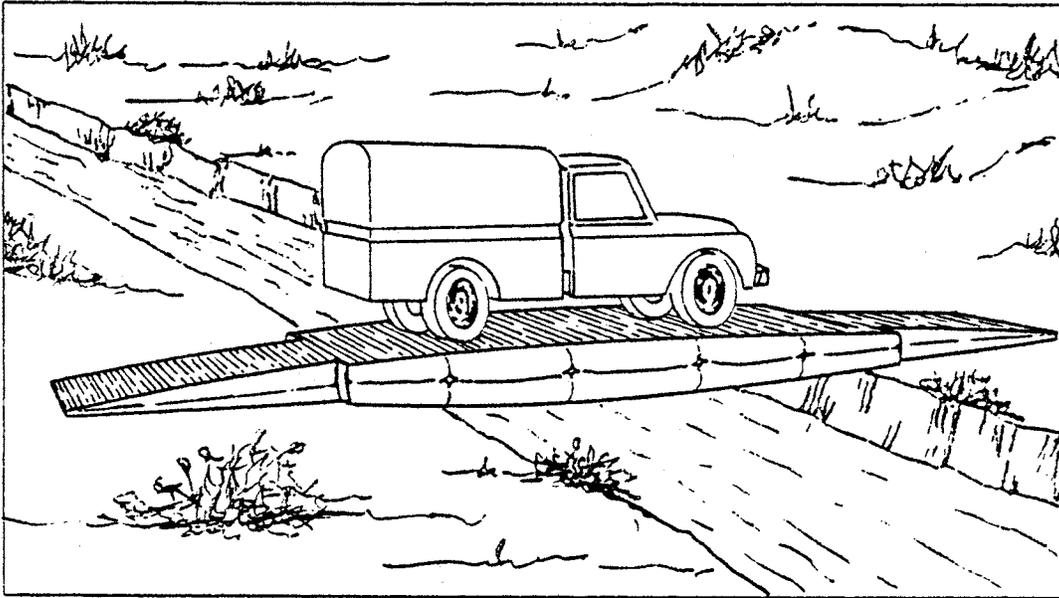


Figure 23

#### Pneumatic bridge

Basically, the structure consists of a series of pneumatic tubes or beams joined together to form a one-lane bridge. Air pressure in the cells is sufficient to support a light vehicle on a span of about 20 ft. Ramps at the ends of the bridge can be of separate pneumatic wedges or other conventional material. A mat placed on top of the pneumatic bridge resists wear and tear on the fabric.

For special situations, the concept of an inflatable bridge is intriguing, as the bridge can be collapsed into a small package for transport and be inflated with an air compressor for almost immediate use. As fabrics of high strength are developed, large air pressures of pneumatic beams can be used to span large distances for heavy loads. Deflections, however, will remain much larger than for conventional bridges.

Further information on this bridge can be obtained from the Military Vehicles and Engineering Establishment, Christchurch, England.

### Conclusions — Relocatable Bridges

It is seen that the military is at the forefront of technological development regarding relocatable bridges. Of the thirteen types of bridges described, most were developed for military use. However, military bridges, particularly the newer ones, are designed to meet complex needs not normally required for civilian applications. Thus, they tend to be expensive, though very innovative.

Generally, those relocatable bridges developed by private industry for civilian use are more conventional in appearance and construction. Their costs, therefore, are much less than those of the new, sophisticated military bridges and are comparable to those encountered in the construction of normal short spans.

The folding bridge concept proposed by the writer is an attempt to utilize some of the high technology developed by the military for civilian application. High technology construction, in all probability, will always be more expensive than conventional bridge construction on a first cost basis, but the gains in adaptability could make it cost-effective when measured against time and traffic disruption factors.

None of the bridges cited may be considered the ultimate answer, so much development is yet to be done. As a guide to future development, the following criteria for the "ideal" relocatable bridge should be met

1. Strong (adequate for civilian loading of HS15 or HS20 and military loading of 60 tons)
2. Durable (adequate for several years of service with little maintenance)
3. Lightweight (capable of being handled by a party of workers or a small construction machine)
4. Economical (no more expensive than a conventional fixed bridge)
5. Capable of easy and quick erection and dismantling
6. Capable of variable geometry (as length, grade, skew, vertical curve, horizontal curve, and superelevation)
7. Esthetically pleasing when erected
8. Capable of compact storage and transportation

## ACTIVELY CONTROLLED BRIDGES

The concept of active control of the behavior of bridge structures is relatively new. However, active control as such is not new in other areas of engineering. In transportation engineering it has been applied successfully to guidance systems of ships, planes, and missiles. In communication engineering it has made possible such things as television and space transceiving satellites. In mechanical engineering it is used extensively in the operation of many types of machines and motors.

Stated briefly, active control is that arrangement, or automatic chain of events, in which (a) selected information is first detected by a sensor, (b) this information is then sent to an analyzer, (c) and the analyzer output activates or energizes a mechanism which effects the desired control. Throughout history, bridges have been built as passive systems in which the mass of the materials reacts passively against whatever forces are imposed upon it. Its response to forces are essentially fixed by the configuration and the properties of the materials. In active systems, the response can be made to vary with time and conditions.

As bridges become longer, their flexibility tends to increase, causing greater vibration and dynamic problems. Additionally, as span lengths increase, the ratio of dead to live load tends to increase, resulting in the inefficient use of materials. Active control systems offer a totally new way of reducing both the dynamic effects and the dead to live load ratios of long span structures. The system also offers the possibility of controlling deformations caused by temperature, creep, shrinkage, and the like.

This section of the report on actively controlled bridges has three main headings; namely, Theory, Hardware, and Conclusions, with supplemental reference listings and an appendix. Under "Theory", a synopsis of recently developed mathematical theories relating to active structural control is presented. Because much of the basic theory is applicable to all forms of structures, theories relating to buildings, towers, spacecraft, and the like are presented along with those specifically intended for bridges. Under "Hardware", examples of physical experiments, applications, or possible hardware are given. Here, also, hardware of any sort that may have relevance to bridges, directly or indirectly, is described. Under "Conclusions", an overview of the state of the art is discussed along with further research that is needed.

### Theory

The essence of the theories relating to active structural control is presented here as developed by various researchers. References to their full works are also listed for those wishing to study the details.

#### Yao, James, T. P.

References 1-5 list the publications of Professor Yao as related to active structural control, all of which were funded by the National Science Foundation. In his paper "Concept of Structural Control"(1), Yao sets forth the feasibility of active structural control systems for use in the dynamic control of tall buildings subject to wind or seismic forces. Figure 24 shows a simplified feedback system as might be applied to a multistory building. Although no mathematics are presented in this paper, Yao sites a considerable body of mathematical knowledge in control theory as applied to the field of electronics. The paper cites numerous references on the basic theories of automatic or feedback control.

In the report "Active Control of Civil Engineering Structures"(2), Yao and Tang set up the differential equations of motion for a multistory building with both external and active control forces. Three mathematical solutions are presented for the case of a single degree of freedom (as a one-story building) subject to (a) sinusoidal excitation, (b) random wind force, and (c) an actual earthquake excitation based on the 1940 El Centro, California, seismic data. A two-degree of freedom (as a two-story building) solution is also presented for the earthquake situation. In all these cases, structures with controls exhibit less distortion than those without active controls. Figure 25 is an illustration of the relative displacement of the second floor of a two-story building in the critical first ten seconds of an earthquake, with and without controls. These theories, however, do not consider the specific nature and magnitude of the control forces needed. Such studies remain for further investigation.

Yao, along with Yang, in reference 3 entitled "Formulation of Structural Control" deals with the application of optimum and stochastic control theories to a multi-degree of freedom structure (as a tall building) subject to random loading. Linear differential equations of motion are set up in matrix form and the excitation is described as a Gaussian function (a balanced random loading often referred to as white noise) and as a filtered Gaussian function (more closely resembling wind or seismic forces). Active control forces are assumed to act at each mass point (or story level in the case of a multistory building). To obtain the best

values for the control forces, an optimizing procedure is used based on the Riccati equations (equations describing a special relationship of factors required for optimization). Also used is a performance index criterion which represents a reasonable balance between excessive deformation (representing safety) and energy input (representing economy). Only basic matrix equations are derived in this study, with no numerical examples being presented.

Theories developed by Yao in conjunction with Sae-Ung,<sup>(4,5)</sup> deal with active control of multistory buildings subject to wind loads. In these studies, the control criteria are that of human comfort (represented basically by acceleration limits), excessive deformation, and energy input for the control system. Basic differential equations of motion are set up as for any multiple-degree of freedom structure, with wind being represented by a statistical equation resembling actual gusting wind. Active control forces are assumed as impulses, or step functions, occurring on and off at variable intervals of time. Because of the interaction of random excitation forces with the control criteria, the basic set of differential equations of motion are nonlinear. The Monte Carlo method (an orderly technique to handle a system of probabilistic events) is used to solve the equations. Several numerical solutions to the control of tall structures are presented. Figure 26 illustrates the displacement, acceleration, and control force at the top of a 40-story building subject to a strong and gusting wind force. Beneficial effects of active control are observed.

#### Yang, Jann-Nan

References 3, 6, 7, 8, 9, and 10 describe the work of Professor Yang. These studies were all funded by the National Science Foundation. The theory presented in reference 3 has been previously described in connection with Yao's work. Reference 6, "Application of Stochastic Control Theory to Civil Engineering Structures", is basically a restatement of the theories presented in reference 3, but with several numerical examples for a two-story building subject to earthquake and wind excitation. The results show that horizontal control forces applied at each of the story levels substantially reduce the magnitude of relative displacement of the structure. Results further show that if only one control force is possible, it is most effective at the top story.

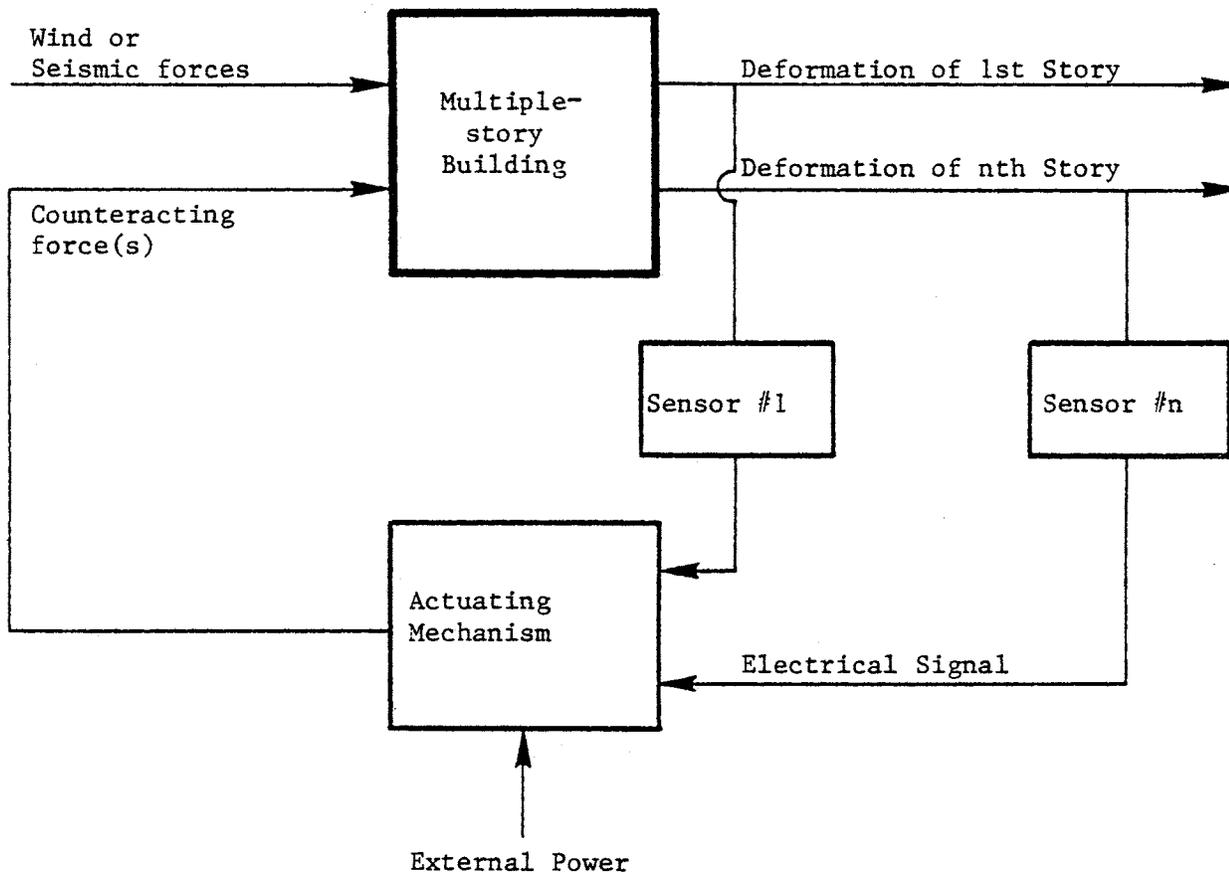


Figure 24

Feedback structural control system

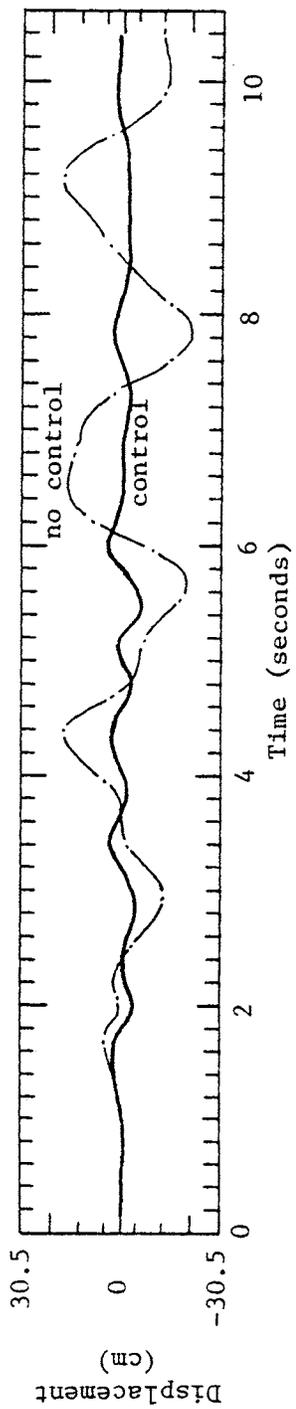


Figure 25

Displacement with and without controls

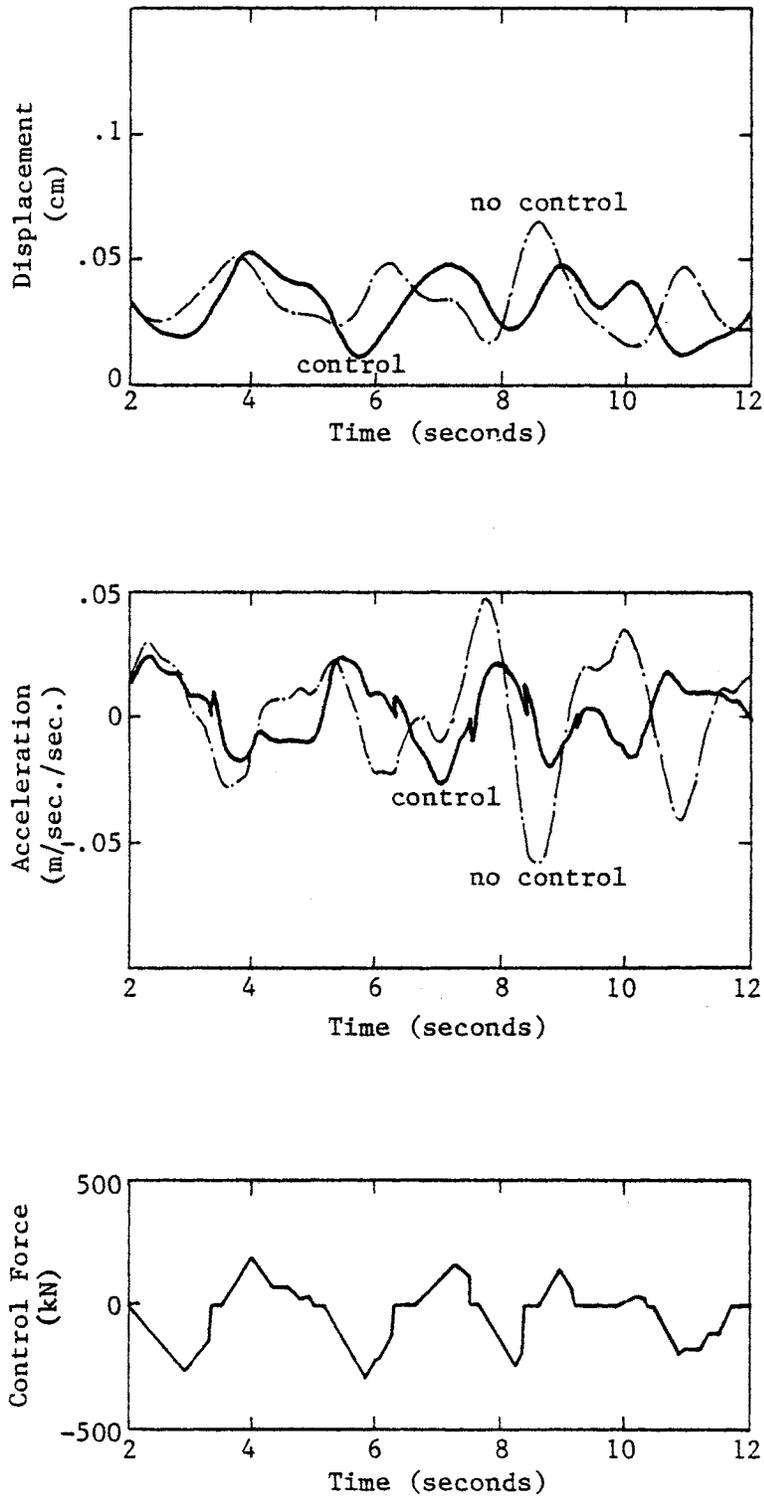


Figure 26

Behavior with and without control

In reference 7, Yang and Giannopoulos investigate a model control theory for structures, in distinction to the "optimum" control theory presented in references 3 and 6. In modal theory, a specific control force location is set, from which a solution to the differential equation of motion may be had in closed form. Various control positions and conditions can be assumed, one at a time, and the final solutions can be compared to obtain the most feasible and desirable system. Several numerical examples are presented in references 7 and 8 in which a tall building is subject to a stochastic (random) wind force. Tendons are assumed to act on the structure at specific locations (as at midheight or at top) such that both a horizontal force and a moment can be induced, as by a hydraulic servomechanism (see Figure 27). Numerical computations show that active control can reduce the magnitude of deformation and acceleration by one order of magnitude for a tendon force of approximately 15% of the total wind force, and that active control forces have far greater moderating influences than does passive clamping. The control position is most effective, in general, when at the top of the structure. However, if a specific mode must be controlled, the active control force location should be put at that position. It also was found that whereas the deformation and acceleration of that mode may be controlled, it could in some cases produce a magnification of other modes. A further conclusion reached in these studies is that active control systems are most effective (from an energy standpoint) for flexible structures. Stiff structures require excessive amounts of control forces.

Yang and Giannopoulos, in reference 8, developed a control theory directed toward the aerodynamic stability of cable-stayed bridges of the type shown in Figure 28. Differential equations of motion of the deck, considering both vertical and torsional deformation, are developed under the excitation of wind and the restoring action of active forces at the positions of the cables. At critical wind velocities a suspension bridge can start to oscillate wildly and go unstable. A method for calculating this critical wind speed is presented for various conditions of active control based on acceleration and velocity. A numerical example using data from the Sitka Harbor cable-stayed bridge in Sitka, Alaska, shows that active control systems do favorably raise the value of the critical wind velocity causing instability or flutter, depending on the amount of control force exerted.

In reference 9, Yang and Giannopoulos extend the work cited in reference 8 to include the power requirement for the active control devices of a cable-stayed bridge. For the Sitka Harbor Bridge, the root mean square of the bridge response can be reduced as much as 40% to 50% with an average power requirement less than 10 h.p. For bridges designed specifically for active control, which would be less stiff statically, the power requirement would be even less to achieve the same measure of control.

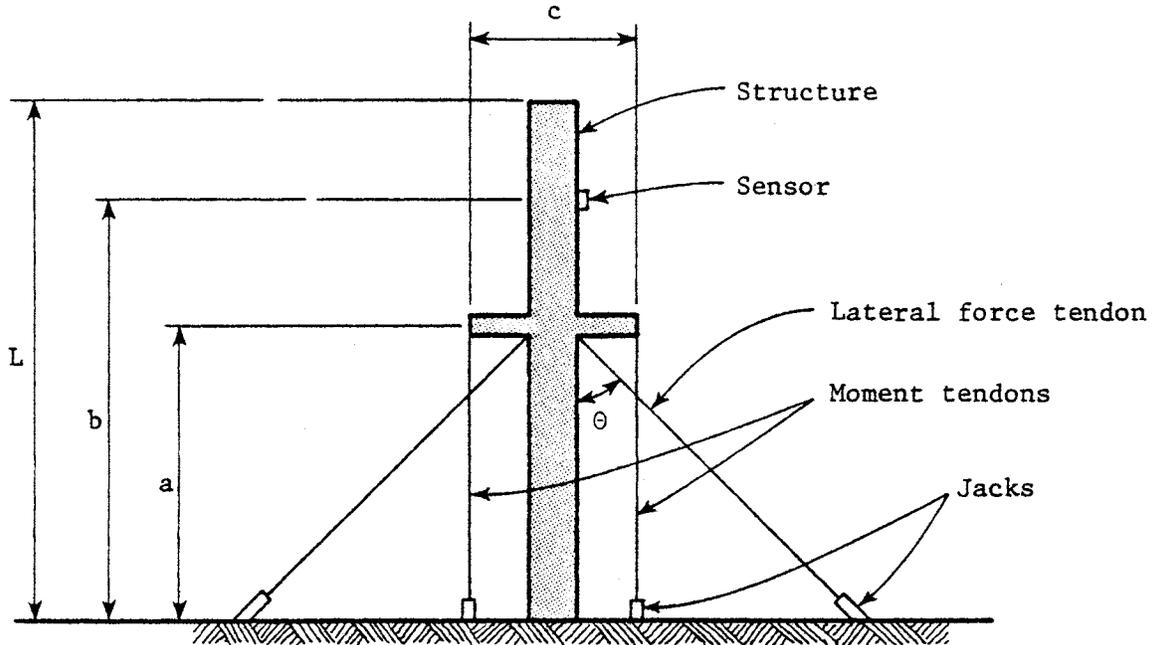
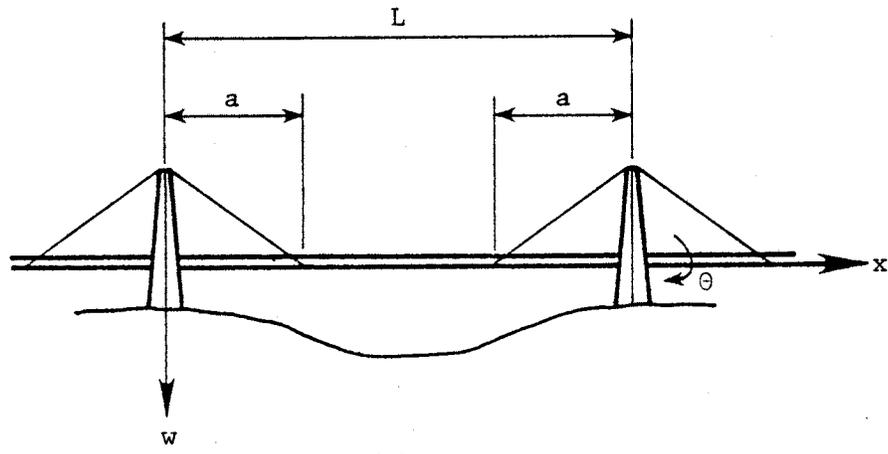
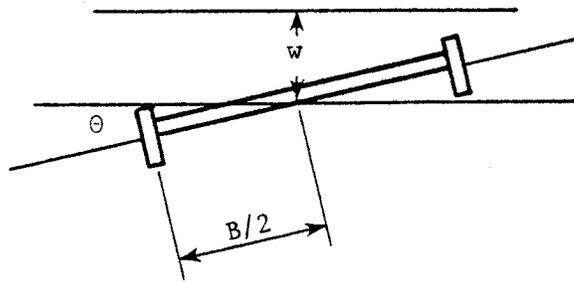


Figure 27

Schematic of tall building with actively controlled tendons



(a)



(b)

Figure 28

Cable-stayed bridge

(a) Elevation

(b) Deflection and torsion coordinates

Soong, T. T.

Professor Soong, with Charlesworth Martin,<sup>(10)</sup> set forth a theory of modal control of a multi-degree of freedom structure. Using a vector theory of dynamics, the authors derive the basic conditions of control needed to alter the vibrating mode or frequency of a multi-degree of freedom structure. Conditions of active external control can be preset by the investigator and alternate solutions can then be obtained for comparison. A numerical example of wind acting on a two-story building is given for explanation. Figure 29 shows the comparative behavior of the structure with no control, control only at the first story, control only at the second story, and control at both stories. It is clear that active control significantly reduces the displacement of the building. Energy requirements to effect these controls are also calculated, showing the least amount of energy needed for control.

Roorda, John

Reference 11, describing the work of Roorda, deals with the active damping of slender masts and towers subject to vibration. The author assumes a condition of a tall, slender structure acted on by a gusting wind and actively controlled by moment tendons. The situation is as shown in Figure 27, except that no lateral force tendons are considered. After the basic differential equations of motion are presented, a solution is arrived at by means of a mathematical Laplace transform. As a practical example, Roorda considers a 70 ft. tall steel chimney 1 ft. in diameter and controlled by a pair of tendons attached to the structure 33 ft. from the base. Under a sustained harmonic lateral wind force, control tendons stressed only to 12,600 psi will limit the deflection of the chimney to an acceptable value; a value that without control would build up to a destructive level.

Leipholtz, Horst H.

In reference 12, Leipholtz and Abdel-Rohman derive equations for the response of a simply supported beam acted on by a moving concentrated load and actively controlled by a set of moments. In Figure 30, a diagram of this arrangement is shown in which the control moments are generated by a tendon. The entire arrangement is a simplified representation of a bridge beam with a moving load. Based on these conditions, mathematical equations of motion are derived in closed form using known methods, where the response may be controlled by displacements, velocity, or acceleration sensors. Figure 31 shows the comparative deflection of the beam at midspan for an example problem, contrasting controlled and uncontrolled behavior. The author's conclusion is that feedback control does

provide a suitable means of improving the structure's response. For best results, careful consideration should be taken of the type and location of the sensor (preferably at the location of the control force) and the dynamic stability of the system for the various modes of vibration.

In reference 13, the beam with the moving load shown in Figure 30 is reanalyzed mathematically using a variation of the modal control method cited in Reference 10. The pole assignment method differs from the modal method in allowing control of any number of modes in any desired form. Numerical examples are worked out using this pole theory. The results, very similar to that in Figure 31, show that a rapid decay of deflection takes place with control by use of this theory.

Leipholz and Abdel-Rohman, in reference 14, develop a closed loop theory of structural control of buildings that simultaneously satisfies criteria for safety and human comfort. Displacement and acceleration are taken as indicators of safety and comfort. Figure 32 illustrates the general process of analysis. The Riccati equation is used to determine optimum conditions. Note that a feedback loop is introduced to adjust the weighing factors so that a balanced behavior of displacement and acceleration can be established. A numerical example of a two-story frame building with cross bracing at each story is presented. The forces in the cross braces are controlled with an active system. The conclusions show that lateral displacements and accelerations under predictable lateral forces can be greatly reduced by an active control mechanism. Random loading conditions were not investigated in this study.

In reference 15, Leipholz and Abdel-Rohman, in collaboration with Victor Quintana (an electrical engineer), restudy the problem of the beam with the moving load shown in Figure 30. This study investigates two ways of optimizing structural control. The first uses closed loop control theory (called regulation) and the second uses a combination closed loop and open loop control law (called tracking). The conclusion reached is that for a structure subject to a known disturbance the tracking method is more applicable. However, for a structure subject to an unknown disturbance, the regulation method is more applicable in that it enables a designer to find the best closed loop control law. In either case, the mathematics of optimal analysis are rather complex and are best used for structures with relatively few modes of vibration.

The beam with a moving concentrated load is used again in reference 16, which examines several secondary effects on the behavior of active control. Considered are the unevenness of the deck, effect of the load being a sprung mass, and the condition of the load being in resonance with the vibration of the beam. In all cases the active control system reduces the severity of the vibration.

The listed studies by Professor Leipholz were done at the University of Waterloo and were sponsored by the National Research Council of Canada.

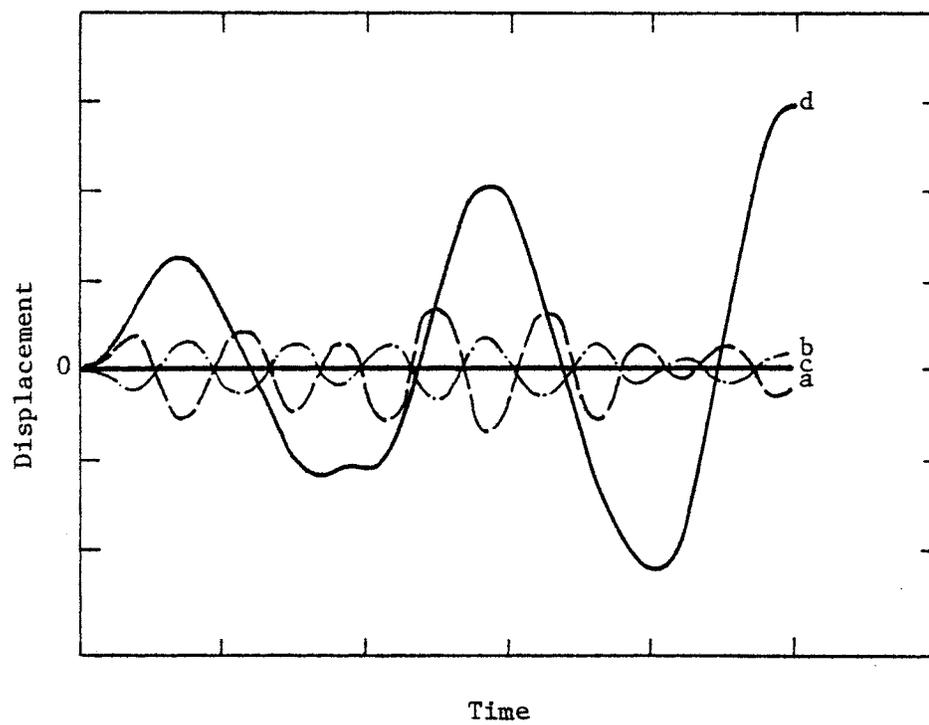


Figure 29

- Displacement of second floor
- (a) Control only at first floor
  - (b) Control only at second floor
  - (c) Control at both floors
  - (d) No control

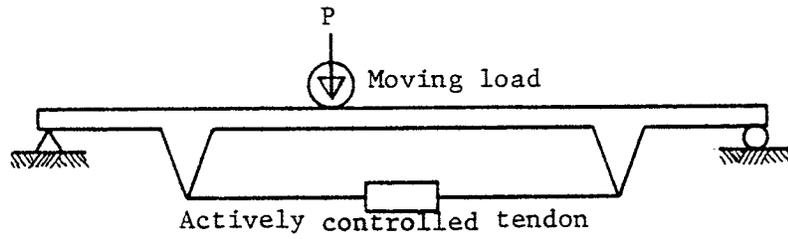


Figure 30  
Actively controlled beam

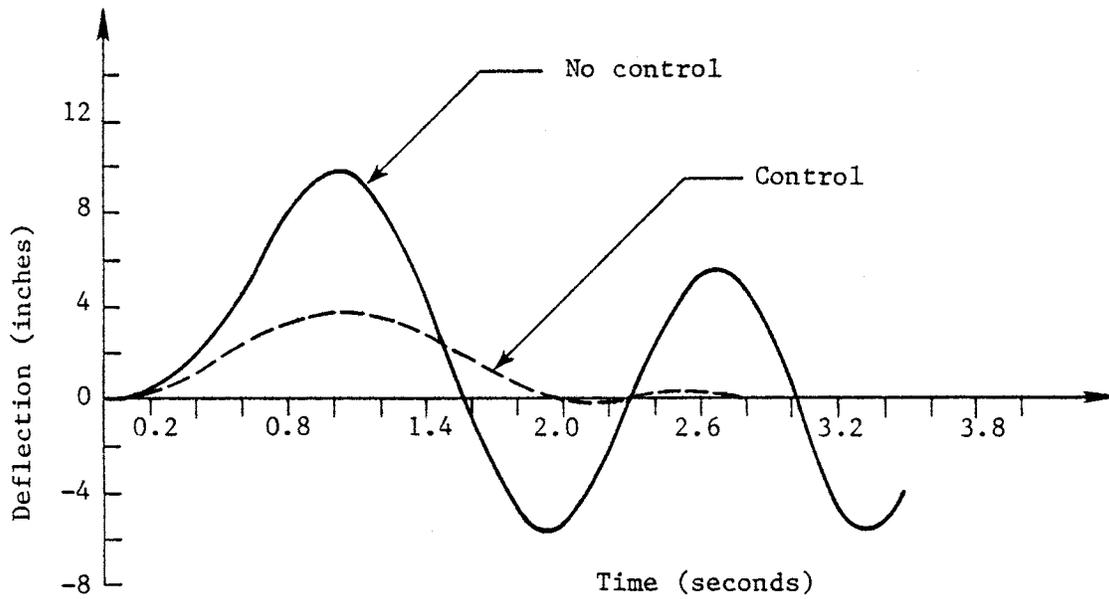


Figure 31  
Deflection response at midspan

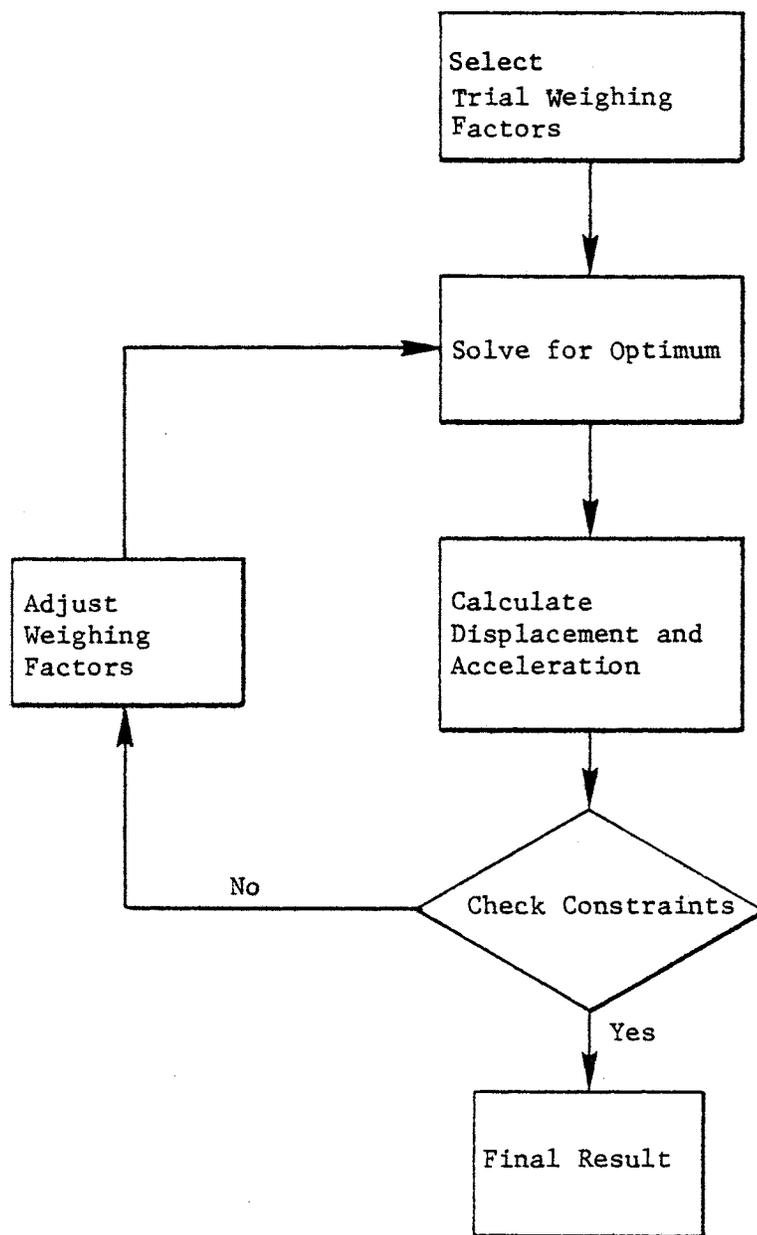


Figure 32

Flow diagram for control analysis

Derby, Thomas F., and Calcaterra, Peter C.

The study entitled "Control of Single-Span Highway Bridge Vibrations" by Derby and Calcaterra<sup>(17)</sup> involves the comparative dynamic behavior of a simply supported girder bridge under the action of a moving vehicle. Four conditions are investigated to reduce vibration; namely rigidizing as increasing the cross section; damping; passive absorbing, as adding a sprung mass with dashpot; and active absorbing. Only the active absorber concept is addressed in this kinetic bridge report. In principle, the active control system involves a mass suspended beneath the bridge at its midspan with a servo-hydraulic jack connected between the mass and the bridge. The jacking force acts automatically in opposition to the velocity of the bridge, thereby serving as an active damper. See Figure 33. Base equations and calculations are presented for the case of a 250 ft. long steel bridge. The conclusion reached is that the active control system is generally the most dynamically effective means of reducing vibration, although it is also the most expensive for a 250-ft. bridge.

McNamara, Robert J.

The tuned mass damper described in reference 18 is a partially active structural control system. In concept, a large mass is positioned in or along a structure, as at the top of a tall building, and is held in position by springs and dashpots damper, as in a passive absorber system. However, the system is activated only under conditions of excessive motion. In reference 18, equations of damped motion are derived for a multistory building illustrating how they may be solved for the case of a determined lateral forcing function or a random stochastic wind force. The results are consistent with the principle that vibration decays more rapidly with damping than without.

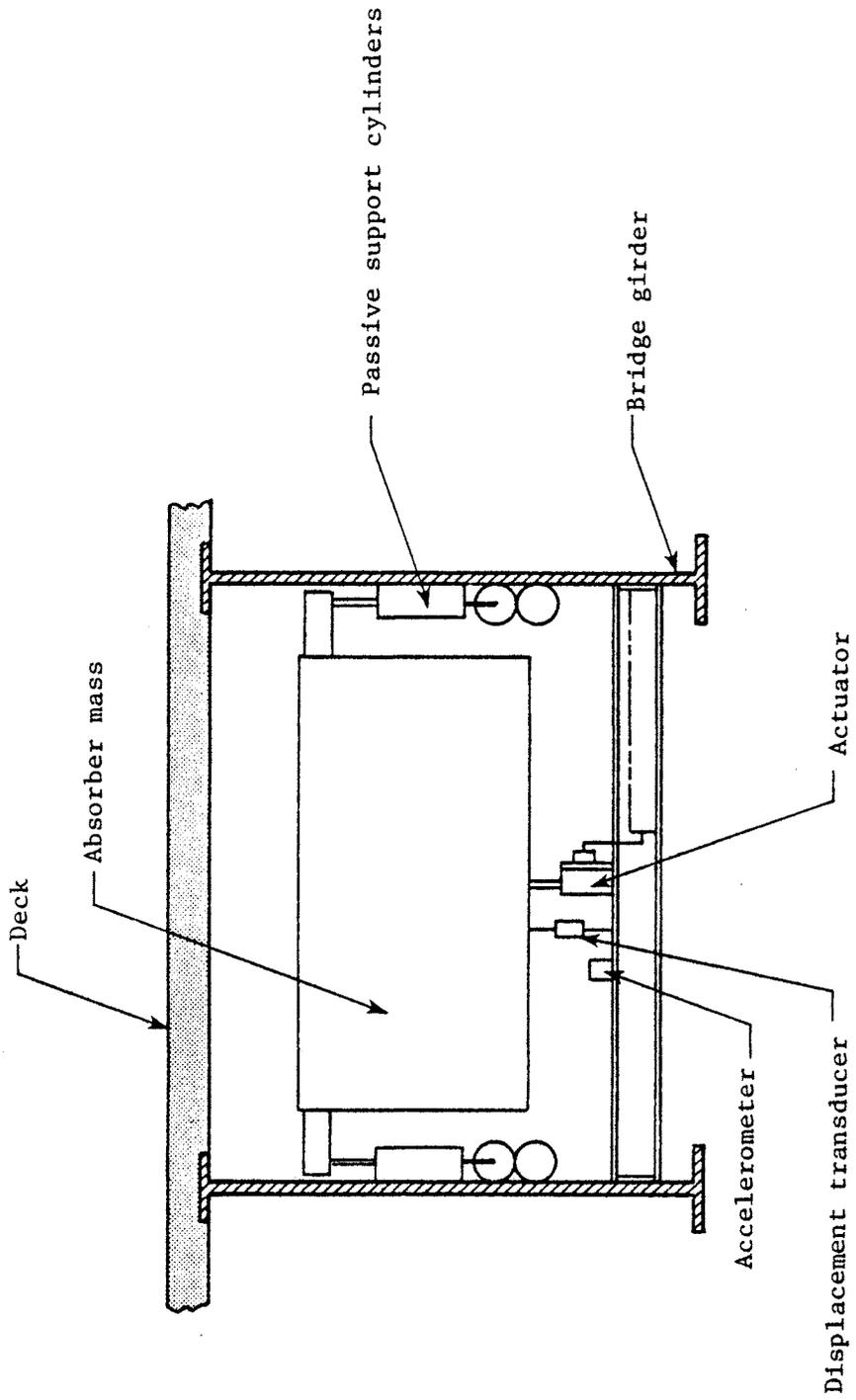


Figure 33

Schematic of active system installation

Authors in Reference 19

In June of 1979 an international symposium on the subject of active structural control was held at the University of Waterloo, Ontario, Canada. A presentation in this report of all the theories explained at the conference would be quite extensive. However, to indicate the general nature of the theories, a listing of select authors with the titles of their papers is here given.

Abdel-Rohman, M. and Leipholz, H.H.E., "A General Approach to Active Structural Control", pp. 1-28.

\_\_\_\_\_, "Automatic Active Control of Structures", pp. 29-56.

\_\_\_\_\_, "Design of Reduced Order Observers for Structural Control Systems", pp. 57-77.

Auloge, J., "Flexure Oscillations of Bridges - Estimation of the Velocity and of the Acceleration by Using Luenberger Observers", pp. 95-106.

Balas, M.J., "Active Control of Large Civil Engineering Structures", pp. 107-126.

Chang, J.C.H., and Soong, T.T., "The Use of Aerodynamic Appendages for Tall Building Control", pp. 199-210.

Hirsch, G., "Critical Comparison Between Active and Passive Control of Wind Induced Vibrations of Structures by Means of Mechanical Devices", pp. 313-339.

Kelly, J.M., "Control Devices for Earthquake-Resistant Structural Design", pp. 391-413.

Klein, R.E., and Salhi, H., "The Time-Optimal Control of Wind Induced Structural Vibrations Using Active Appendages", pp. 415-429.

Lund, R.A., "Active Damping of Large Structures in Winds", pp. 459-470.

Masri, S.F., Bekey, G.A., and Vdwadia, F.E., "On-Line Pulse Control of Tall Buildings", pp. 471-491.

Meirovitch, L., and Oz, H., "Active Control of Structures by Model Synthesis", pp. 505-521.

- Petersen, N.R., "Design of Large-Scale Tuned Mass Dampers", pp. 581-596.
- Roberts, J.W., and Borgohain, M.C., "An Active System for Neutralization of Vibratory Force Interactions in Structures", pp. 613-627.
- Roorda, J., "Experiments in Feedback Control of Structures", pp. 629-661.
- Juang, J.N., Sae-Ung, S., and Yang, J.N., "Active Control of Large Building Structures", pp. 663-676.
- Soong, T.T., and Chang, M.I.J., "On Optimal Control Configuration in Theory of Modal Control", pp. 723-738.
- Yao, J.T.P., "Identification and Control of Structural Damage", pp. 757-777.
- Zuk, W., "The Past and Future of Active Structural Control Systems", pp. 779-794.

#### Zuk, William

The author's approach to a control theory is deterministic and takes into consideration certain practical limitations of possible hardware needed to achieve the theoretical results. For a simple understanding of the theory, imagine a mass oscillating up and down in a gravity field, simulating the deck of a bridge in its fundamental mode. Its displacement would be represented by the graph in Figure 34, designated "no control". A normal amount of damping resulting in a slow decay of amplitude is assumed. However, if an active, vertical control force is applied which is proportional to the displacement, the resulting displacement is reduced much more rapidly, as shown in the graph designated "controlled". Note in Figure 34 that the control force is intermittent, acting only when the displacement is down or positive (below its static equilibrium position), and its velocity is also positive. The effect of the active force is to stiffen the system in its critical portion of the vibrating cycle. In addition, the active force so applied works to decrease downward deflection under slow as well as rapid movements.

Still another feature of the theory is that it provides recovery time for the force actuator. If it is assumed that the force actuator is a cable in a cable-stayed bridge in which the cable is connected to a hydraulic jack equipment can be so designed that the hydraulic pressures can be stored for recycling during the recovery periods. This recycling process will greatly reduce the energy required to operate the system.

Additional details and mathematics of the theory are presented in reference 20, as presented by Thomas Sutter, a graduate student working under the direction of Zuk.

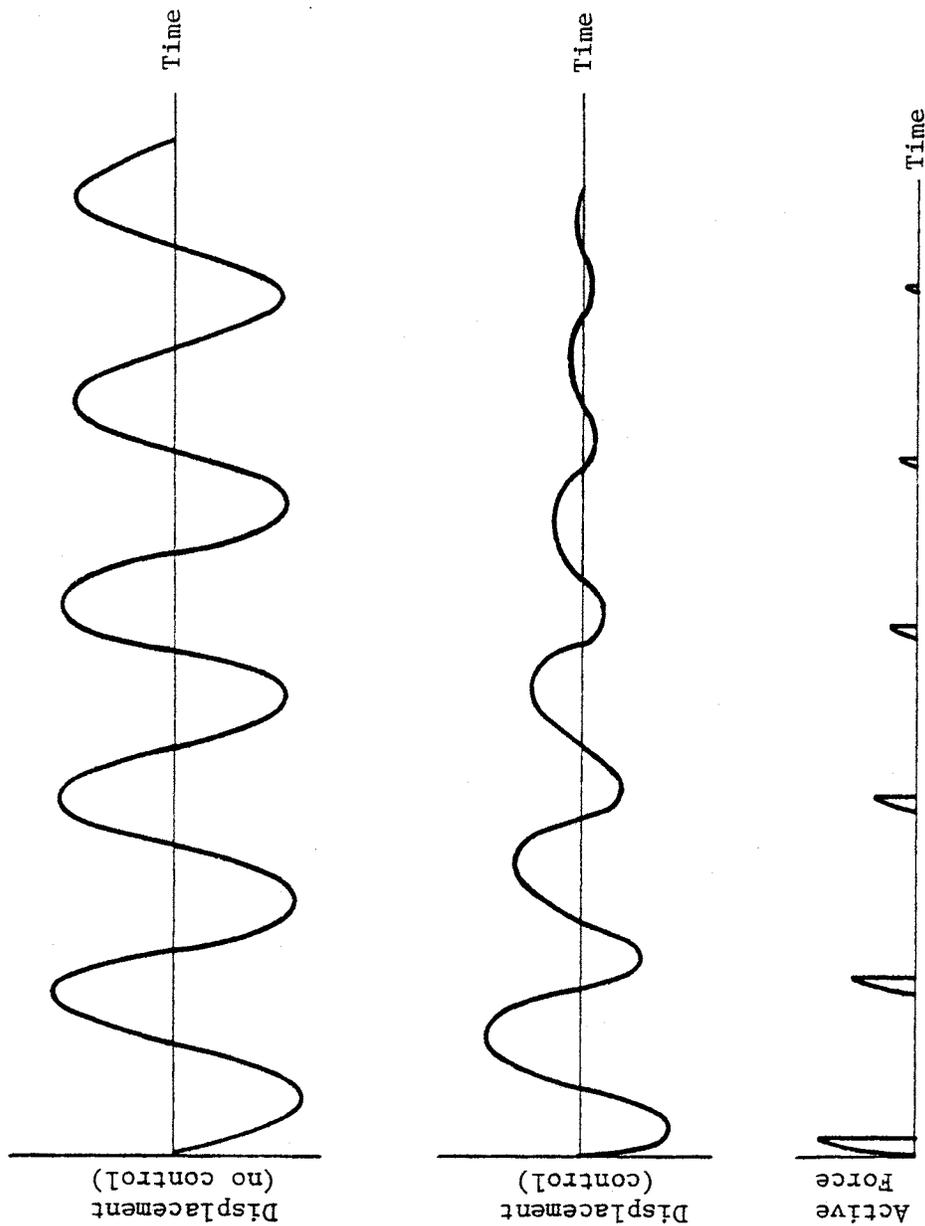


Figure 34  
Comparison of controlled and uncontrolled behavior

Authors in References 21 and 22

Numerous theories are presented in the proceedings of two symposiums on the active control of large flexible structures as cited in references 21 and 22. Although much of these theories could have some mathematical application to the control of bridges, their specific focus is on structures intended for outer space. As such, these theories are not described in any detail here. Rather, only a listing of selected subject titles and their authors is presented.

Balas, M.J. "Active Control of Flexible Systems" (ref. 21).

Balas, M.J., and Canavin, J.R. "An Active Modal Control System Philosophy for a Class of Large Space Structures" (ref. 21).

Lin, J.G., Lin, Y.H., Hegg, D.R., and Keat, J.E. "Output Feedback Control of Large Space Structures: An Investigation of Four Design Methods" (ref. 22).

Caglayan, A.K., Van Landingham, H.F., and Sathe, S.G. "A Procedure for Optimal Control of Flexible Surface Vibrations" (ref. 22).

Bainum, P.M., and Reddy, A.S.S.R. "On the Controllability of a Long Flexible Beam in Orbit" (ref. 22).

Juang, J.N., and Wu, Y.W. "On Dynamics and Control of Large Flexible Structures" (ref. 22).

Johnson, C.R. "Approaches to Adaptive Digital Control Focusing on the Second Order Modal Descriptions of Large Flexible Spacecraft Dynamics" (ref. 22).

Benhabib, R.J., Iwens, R.P., and Jackson, R.L. "Active Vibration Control of a Flat Plate Using Modal Reference Adaptive Techniques" (ref. 22).

Potter, J.E., and Ginter, S.D. "A New Concept in Adaptive Structural Control" (ref. 22).

Sesak, J.R., and Likins, P.W. "A Flexible Spacecraft Control by Model Error Sensitivity Suppression" (ref. 22).

Viswanathan, C.N., Longman, R.W., and Likins, P.W. "A Definition of the Degree of Controllability - A Criterion for Actuator Placement" (ref. 22).

Hughes, P.C., and Skelton, R.E. "Controllability and Observability for Flexible Spacecraft" (ref. 22).

- Elliott, L.E., and Iwens, R.P. "Performance of Robust Output Feedback Controller for Flexible Spacecraft" (ref. 22).
- Skelton, R.E., and Hughes, P.C. "Spacecraft Control Design by Modal Cost Analysis and Synthesis" (ref. 22).
- Strunce, R.R., and Henderson, T.C. "Application of Modern Modal Controller Design to a Large Space Structure" (ref. 22).
- Balas, M.J. "Enhanced Modal Control of Flexible Structures Via Innovations Feedthrough" (ref. 22).
- Meirovitch, L., and Oz, H. "Control of Large Flexible Spacecraft Possessing Ignorable Coordinates" (ref. 22).

### Hardware

In this section, three categories of hardware are discussed; namely, those already installed on full-scale structures, those made for laboratory experiments, and those proposed or possible and yet to be made. The hardware described generally is that which may have application for bridge structures, directly or indirectly. As mentioned previously, many successful pieces of hardware have been developed for active control of communications, ships, planes, and missiles. This type of hardware is not described in this report as the control forces on structures are magnitudes greater than those required for guidance systems, thus placing hardware for bridges in a different classification. However, closely related to bridges are other structures as buildings and towers, and so these types of hardware applications are presented.

### Installations

Fundamental to all active control systems is the sensor hardware. The mounting of sensors on structures to measure and monitor movement is becoming a routine matter. Hundreds of bridges have been installed with strain gages of various sorts, many recording the data automatically. Accelerometers, accurate to 1/1,000 of the acceleration of earth's gravity, are mounted on some bridges. Velocity sensors generally of the seismometer type for measuring earthquake activity also are commonly used on structures. Recently, optical or laser beams have been used in tall structures for the direct detection of motion. A notable installation of a laser beam sensor is in the Canadian National (CN) tower in Toronto. Processing of its information is by means of a mini-computer located at the base of the tower. A description of this installation, as well as a description of other forms of sensors, is given in reference 23. A number of companies manufacture various types of sensors intended specifically for buildings

and bridges. Although further improvements in accuracy and reliability are always to be desired, sensors to measure strain, displacement, velocity, and acceleration may be considered at this time a practical reality.

Full-scale installations of active control systems on structures are but few as of this date. In the 1960's the U.S. Navy built a large communications antenna in western Australia. The antenna consists of long suspended cables covering an area 2 mi. in diameter. As changes in the sag of the cables caused by temperature changes, wind, and the like affect the efficiency of the antenna, an active control system was developed to keep the sag constant. Electrical strain gage sensors were placed on the cables to detect changes in strain (which can be related to sag). Sensor signals generated are processed electrically and sent to a motor which turns a large reel to which the cables are attached. Thus, as a sensor detects an additional sag, the motor reels in the cable an amount necessary to adjust it. For a detected decrease in sag, the reel pays out the cable. Each winch or reel is capable of exerting a line pull of 50,000 lb. All electrical equipment is designed to operate in the environment of equatorial heat, humidity, dust, and fungus. In all, 35 mi. and 600 tons of cable are automatically controlled. Additional information on this naval installation may be found in reference 24, pp. 35-36.

Two installations of a large tuned mass damper (TMD) control system exist, one in the Citicorp high-rise building in New York City and the other in the John Hancock high-rise building in Boston. They are not totally active control systems in the sense that controlled forces are directly applied to the structure, but are active in that a special damping system operates in a variable and controlled manner. Only a limited active force is developed in this system as installed, but with modifications the system could be made fully active. Details of this installation are explained in reference 25, and a short description of it is given here. The TMD systems on both buildings are similar, except that in the Citicorp building there is one and in the Hancock tower that are two.

The heart of the system is a large solid mass located at the top of the structure. In the Citicorp building the mass is a 400-ton block of concrete and in the Hancock Tower, the mass is 300 tons of lead and steel. Their function is to reduce the vibrational sway of the building. Constrained by a set of nitrogen gas springs (acting like pistons) and a set of hydraulic dampers (oil dashpots) the mass is allowed to move horizontally in either direction. When a critical acceleration of the building occurs, as due to wind forces, the concrete mass is lifted off its base by a thin film of oil and allowed to "float" or react in opposition to the vibration of the structure in its fundamental mode. A computer automatically controls the springs and dampers through

servovalves to achieve the optimum reduction in sway of the structure. The installations are working well and up to expectations.

Two tuned mass dampers are also installed in the CN tower in Toronto; however, these are relatively small as they are intended to control only the higher modes of vibration.

A very sophisticated active structural control system is installed on the wings of the new L-1011 Lockheed TriStar jetliner. Normally, aircraft wings must be passively designed to resist the vibration and flutter they are subjected to in flight. On the L-1011, special ailerons on the wing are added to move automatically in a controlled manner by pistons to generate aerodynamic forces to oppose certain critical vibrations of the wing. Dynamic forces on the wing are thereby reduced. In the case of the Lockheed TriStar aircraft, the wing loading is reduced so much that 9 ft. of length could be added to the wing without any increase in structure. The result is a considerable saving in weight, a very critical factor in aircraft.

### Experiments

Because of the newness of the subject of actively controlled structures, experiments relating to the subject are very few at this time.

In reference 26, Ranulf Gras at the Massachusetts Institute of Technology describes a relatively simple experiment of a small, simply supported beam whose deflection was actively controlled. The beam was so made that it consisted of two joined metal strips, each with a different thermal property. When loaded, a normal beam will deflect; however, this bimetallic flexural member was connected to a controlled source of electricity. As the beam tended to deflect downward under an applied beam load, electricity fed to the top metal strip caused it to heat and expand, thus counteracting the downward deflection caused by the load.

In reference 19 (pp. 629-661), John Roorda at the University of Waterloo (Canada) presents the results of experiments on several beams and columns actively controlled.

In an experiment on a 20 ft. long king post trussed beam, Roorda attached an automatically controlled hydraulic jack on the tendon below the beam. Excitation was by means of an unbalanced rotating mass located at the center of the beam. An accelerometer sensor was also located at the center. By adjusting various parameters, the dynamic displacement was reduced 85% over the uncontrolled displacement.

In an experiment on a 16 ft. tall column excited by a harmonic lateral force at the top, active controls again reduced the

displacement 85% over the uncontrolled condition. The column was mounted and controlled as shown in Figure 27, with the exception of the sloping lateral force tendons. Cross-arm locations, at 10 ft. and 13 ft. from the base were used. Various accelerometer sensor locations also were tried for optimum performance. Although excellent control was manifest on the first mode of vibration, some instability did occur on the higher modes.

The use of an electromagnetic instead of hydraulic jack for control was tried on a cantilever beam 42 in. long. The excitation force, accelerometer sensor, and magnet were all located at the free end. Due to the almost instantaneous response of the electromagnet, a reduction of dynamic displacement of 99.8% was achieved, as compared to uncontrolled displacement.

Roorda's conclusion is that although the electromagnet produced the best results, from a practical point of view for a large structure, tendons and hydraulic jacks are better. He further notes that additional studies need to be done on the possible instability of higher modes of vibration.

Numerous experiments on flutter suppression of wings and tails on aircraft have been performed by the aerospace industry in recent years. Reference 27 is listed as being a typical description of the experiments. In this experiment, a model of an aircraft wing, as shown in Figure 35, was made with actively controlled ailerons on both the leading and trailing edges. These aileron controls were actuated by hydraulic pistons to rotate up or down as determined by a system of sensors, servovalves, and an analog computer. The entire model assembly was placed in a wind tunnel for testing. With no control, the wind fluttered as indicated in Figure 36; but with the control system on, flutter essentially was eliminated. This too is shown in Figure 36.

### Proposals

Unlike actual installations or experiments on active structural control, proposals and concepts for the application of structural control systems are relatively numerous. This interest is, as expected, in any emerging field showing great promise. In time, it is expected that many of the proposals will indeed become realities.

The MTS Systems Corporation, which built the tuned mass dampers used in the Citicorp and Hancock buildings cited in reference 25, has proposed the use of a fully active system on buildings as an extension of the partially active system already developed. See reference 28. Comparative power requirements have been made and it is found that the added power requirement is well within reason to achieve a significant performance improvement.

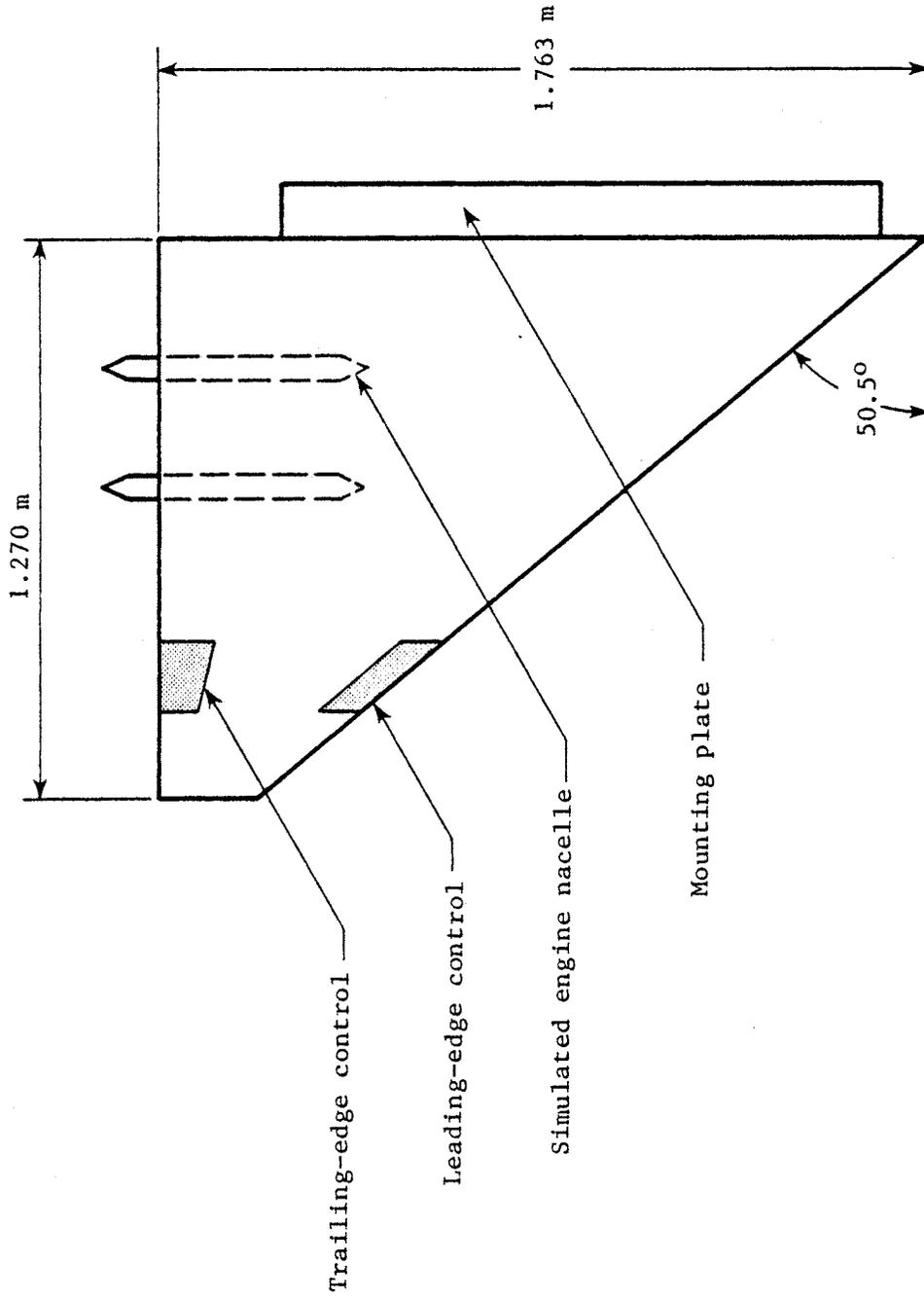


Figure 35  
Drawing of delta-wing model

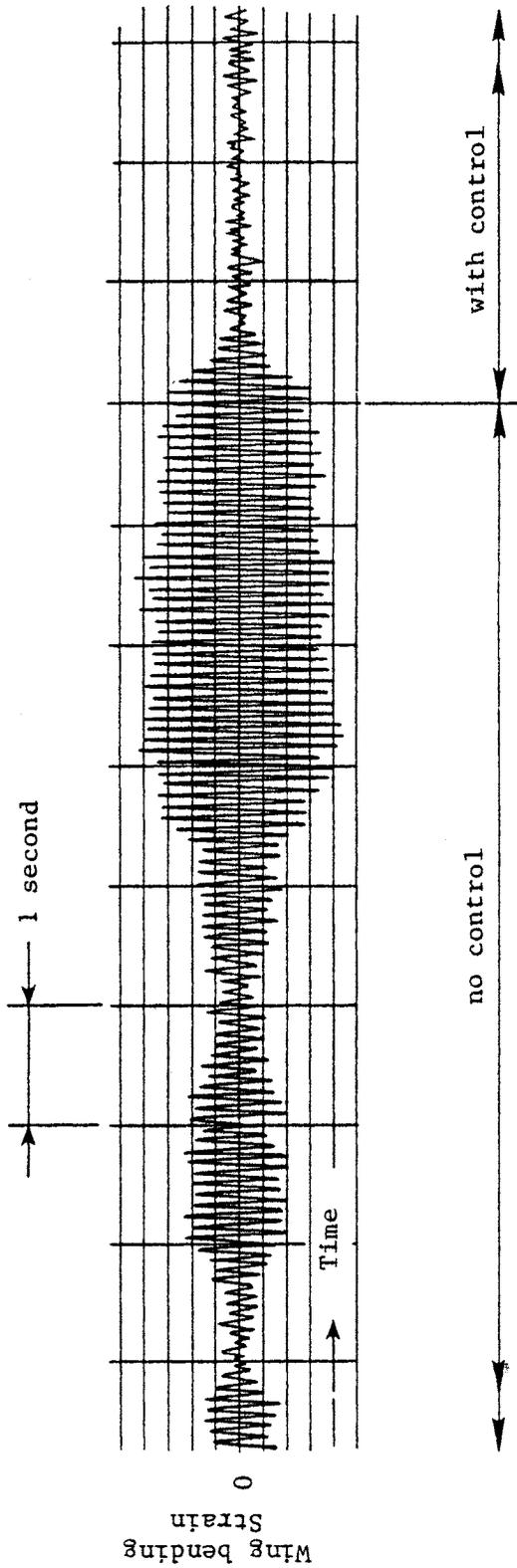


Figure 36

Time history showing effectiveness of wing flutter suppression system

Whereas the MTS concept employs a large mass to generate inertial forces, Lev Zetlin, a consulting engineer, in reference 24, pp. 37-39, has proposed the use of steel tendons connected to hydraulic jacks to induce active control forces in tall buildings. The system was seriously considered for two tall structures; the first, a 1,000 ft. tower in Milwaukee, and the second, a 2,500 ft. tower in New York City. Figure 37 is a schematic view of the Milwaukee tower. It is estimated that millions of dollars in materials cost could be saved using the active control system.

In reference 29, p. 16, Professor James Yao suggests that certain types of structures, as off-shore drilling towers, can be dynamically stabilized by means of steam or water jets. The horizontal reactive force of high speed jets placed strategically on the tower and actively controlled could stabilize unwanted tower movement with considerable savings in structural material.

Still another way to generate active control forces is to use the energy of the wind, particularly if the aggravating force on the structure is the wind itself. Professor T. T. Soong at SUNY-Buffalo and Professor R. E. Klein at the University of Illinois, Urbana, have proposed aerodynamic appendages as moveable vanes or deflectors attached to structures. These appendages would be automatically controlled so as to develop aerodynamic forces acting against the sway or vibration of structures such as tall buildings and long-span bridges. Very little outside energy would be required for this system as most of the energy needed for control would be derived from the wind itself. Further information on the studies of Soong and Klein may be found in reference 19; pp. 199-210 and 415-429, respectively.

In reference 29, p. 13, Professor Horst Leipholz of the University of Waterloo, Canada, proposes the use of active control to keep the foundations of buildings from settling. Large jacks would be built into the foundations of structures that may rest on poor soil. As the foundations settle, the jacks would automatically correct the settlement. With such a system, structures that could not otherwise be constructed on poor soil may be made feasible.

Another proposal concerning foundation stability is made by Professor Masanobu Shinozuka of Columbia University. In reference 29, pp. 13-14, the proposal is made to build large, open bottom platforms for floating on water. On these platforms, one could construct buildings, power plants, or even airports. To stabilize these platforms, Shinozuka plans experiments in which air is pumped into the voids under the platform (between the deck and the water) in such a controlled manner that the platform remains stable despite action by wind and waves.

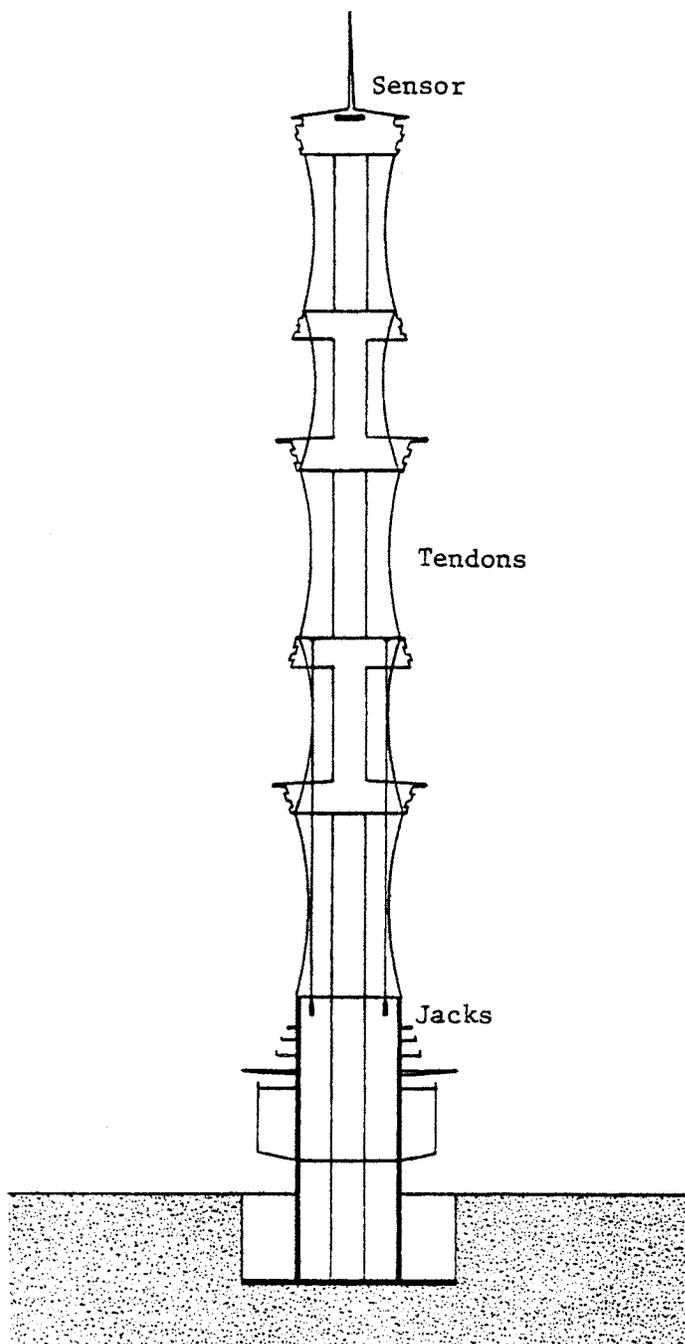


Figure 37

Proposed tower employing automatically  
controlled stressing tendons

In reference 24, p. 39, and reference 30, p. B-9, the author (William Zuk) discusses the use of actively controlled tendons as they may be feasibly used to control undesirable movements in long-span bridges. Although tendon control is possible in any bridge form (as truss, girder, or suspension), its most direct use is for cable-stayed bridges. Existing or supplementary cables between the deck and the mast could be fitted with hydraulic jacks. These jacks would be operated by a servomechanism to control deck deflection. Alternates to the hydraulic jack, as a linear modifier on the cables, are suggested in reference 24, pp. 43-44; listed are such devices as liners, reels, screw jacks, and thermal contraction and expansion units.

On a somewhat different kind of structure, an elaborate proposed control system for a 10-m diameter, multiple mirror telescope is being considered by astronomers and physicists at the University of California (see reference 29, p. 14). Each of the 54 mirrors in this telescope must be kept in position to a tolerance on one-tenth the wave length of light, despite all influences due to gravity, wind, and temperature. To achieve this demanding tolerance, an array of 288 sensors and 162 actuators on the mirrors are to be installed. The telescope's own computer would convert the input of the sensors to commands to the actuators to keep each mirror at its desired position.

### Conclusions

In the last few years, there has been a small but growing interest in the active control of large structures as buildings and bridges. Active control in other areas of technology as communication and transportation has proven to be successful, and indeed has allowed for the development of totally new types of hardware not possible without it. Encouraged by the success of active control in other areas, a number of civil engineers are beginning to study how active control systems may be used to minimize structural distortion or increase structural strength without the expenditure of large amounts of material or energy. The U. S. National Science Foundation (and to a lesser extent the National Research Council of Canada) have provided numerous monetary grants for basic research in this area with the result that the United States has taken the lead in its development.

Mathematical theories specifically relating to large structures, largely drawn from the mathematics of electronic control systems, have been developed. These theories all show the validity of using active systems to control structures, although more mathematical research is needed to analyze specific conditions of loading and structural configuration. Most existing theories were developed for building forms, although some also apply to bridge forms as girders and cable-stayed types.

At this stage in the development of the subject, experiments and field installations are but few. The tuned mass damper system designed for the Citicorp and Hancock buildings may be considered to be the only field installations of an automatic structural control system on a large structure. However, many designs for experiments or full-scale installations are being seriously proposed. Some of the proposals are quite novel and promise to provide breakthroughs in the design of large flexible structures using active rather than passive systems. Engineers working on structures for outer space, as orbiting space stations, find that only through active structural control systems are many such large space structures feasible.

As more and more engineers are becoming interested in this new approach to structures, hard evidence is being built up for the use of active structural systems. At this point, developments for buildings, towers, and bridges are proceeding essentially in parallel; but in time it is expected that work in the area of bridge control will branch off and become a subject in itself. Information is sufficient at this time to indicate that actively controlled bridges are a viable field of research. However, much more investigation at both the theoretical and practical levels is needed before the first fully actively controlled bridge can be built and made reliably operational.



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