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AN ANALYSIS

OF THE

U. S. ARMY

LIGHT VEHICLE / FOOT BRIDGE

DESIGN

by

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May 1990

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ABSTRACT

This report describes an analysis of the U. S. Army's Light Vehicle/Foot Bridge (LV/FB), a lightweight tactical bridging system currently being developed at the U. S. Army Belvoir Research, Development, and Engineering Center (BRDEC) at Fort Belvoir, Virginia. The LV/FB is a modular space frame constructed of aluminum alloy tubing. The deck of the bridge is a flexible composite membrane, composed of Kevlar-49 and E-glass fibers embedded in a neoprene matrix. BRDEC has nearly completed the design for the LV/FB superstructure; however, the quantity and orientation of the composite fibers in the membrane deck have not yet been determined. The intended load capacity of the structure is Military Load Class 7 (MLC 7). Design loads are as specified in the <u>Trilateral Design and Test Code for Military Bridging and Gap-Crossing Equipment.</u>

Analysis of the LV/FB is performed in two major phases. The first phase is an investigation of the behavior of the composite membrane deck. Nonlinear and linear finite element analyses are used. The principal objective is to determine how the behavior of the membrane is affected by the orientation of Kevlar-49 and E-glass fibers The second phase is an investigation of the global behavior of the entire structure. subjected to MLC 7 design loads. Nonlinear and linear finite element analyses are used to determine maximum stresses and deflections in critical structural members.

The results of the first phase indicate that the fiber orientation in the composite membrane deck has a substantial effect on load distribution characteristics, fiber stresses, and maximum deflections of the membrane. Based on these observations, an optimum fiber configuration is recommended.

Based on the results of the second phase, it is concluded that the current LV/FB design does not meet the requirements for MLC 7, as defined in the Trilateral Code. Computed stresses in the superstructure exceed allowable stresses by a substantial margin at several locations. The actual capacity of the structure is estimated to be approximately MLC 5. The report concludes with a series of recommended design changes, which might be used to increase the load capacity to MLC 7.

1. INTRODUCTION

1.1 Background

In recent years, the United States Army has identified a critical requirement for a lightweight, portable tactical bridging system which is suitable for use in Light Infantry Divisions.

The Army's current force structure includes twenty-eight combat divisions, four of which are classified as Light Infantry Divisions [20]. These 10,000-man units are organized and equipped for rapid deployment anywhere in the world. To facilitate air transport, Light Infantry Divisions have few heavy armored vehicles; rather, they are equipped primarily with light trucks, which can be easily and efficiently carried in cargo aircraft [8]. The Army's standard light truck is the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV), a four-wheeled utility vehicle with $1\frac{1}{4}$ ton load-carrying capacity. Though the HMMWV's off-road mobility is quite good, the vehicle is not capable of negotiating steep slopes or crossing water obstacles.

Most Army divisions are equipped with specialized, portable tactical bridging equipment to provide a means for crossing such obstacles; however, none of this equipment is suitable for use in Light Infantry Divisions. Without exception, the tactical bridging systems currently in the Army inventory are too bulky and too heavy for effective employment in light units. These bridges must be transported and emplaced by large cargo trucks or tanks. They are designed to be crossed by armored vehicles and thus have far higher load capacity than is required for the lightweight HMMWV [12]. Furthermore, few of these systems can be easily transported by air; thus they are generally not compatible with the Light Infantry Division's requirement for rapid deployment capability.

In response to this requirement, the Bridge Division of the U.S. Army Belvoir Research, Development, and Engineering Center (BRDEC) at Fort Belvoir, Virginia, is currently developing a new, lightweight tactical bridging system. The design, called the Light Vehicle/Foot Bridge (LV/FB), is both unique and innovative. The superstructure of the bridge is a modular space frame constructed of lightweight aluminum alloy tubing. The bridge's most novel feature is its removable deck, a flexible composite membrane, composed of Kevlar-49 and E-Glass fibers embedded in a neoprene matrix. When erected, the bridge spans 35 feet. When not in use, it can be folded and carried on a small trailer. The entire system, including the trailer, weighs less than 3400 pounds.

As of the writing of this report, the design of the Light Vehicle/Foot Bridge is not complete. The configuration of the superstructure has been established, but the section properties for the membrane deck have yet to be defined. (The section properties pertinent to this report are the membrane thickness, and the quantity and orientation of Kevlar-49 and E-glass fibers.) Defining these properties has proved to be a particularly challenging task. The concept of using a thin, flexible membrane to support a vehicular load is rather unorthodox. The behavior of such a membrane is neither fully understood nor easily analyzed. Nonetheless, the adequacy of the entire LV/FB design cannot be fully evaluated until a reasonable analytical framework is developed for the membrane deck, and reasonably accurate section properties are established.

1.2 Purpose

The purpose of this report is to present the results of an analysis of the United States Army's Light Vehicle/Foot Bridge design, and to recommend additions and changes to the design.

1.3 Research Objectives and Scope

The specific objectives of this analysis of the LV/FB are to:

- (1) Establish section properties for the composite membrane deck.
- (2) Determine the effects of different fiber orientations on the behavior of the membrane.
- (3) Select an optimum fiber orientation.
- (4) Investigate the global behavior of the LV/FB, subjected to design loads under normal operating conditions.
- (5) Evaluate the adequacy of certain critical members in the bridge superstructure. (Critical members are specified in Section 2.4 of this report.)
- (6) Develop recommended design changes, if required.

These objectives effectively define the scope of the research described in this report. To a large extent, the scope of research has been dictated by the immediate needs of the engineers at BRDEC. As they complete the LV/FB design and prepare to construct a prototype, BRDEC's engineers are attempting to achieve each of these objectives. The research described in this report is intended to provide an independent verification of those efforts.

This investigation is not exhaustive. Certain aspects of the LV/FB design

clearly warrant further study, but are beyond the scope of this project. They are as follows:

(1) This research is not intended to provide a detailed design for the composite membrane deck. Membrane section properties are developed only to facilitate further investigation of the entire structural system. Specific aspects of the membrane design are not considered.

(2) This research focuses on the global behavior of the LV/FB, subjected to normal design loads. Detailed investigation is performed only for certain critical structural components. Other components are treated only in general terms, or are not treated at all.

(3) Only static analysis is performed; dynamic behavior of the structure is not considered.

(4) Detailed analysis of connections is not performed.

(5) Fatigue performance of the structure is not considered.

(6) Instability of structural members is not considered.

(7) Behavior of the structure under abnormal loading conditions (such as overload and support settlement) is not considered.

1.4 Analytical Approach

1.4.1 General

The general approach used to analyze the LV/FB is dictated largely by the characteristics of the structure. Because the bridge is a highly indeterminate, threedimensional structure, finite element analysis is used extensively. Furthermore, the complex behavior of the composite membrane deck dictates that nonlinear finite element methods be employed.

Nonlinear finite element analysis is quite costly, in terms of both computer resources and the analyst's efforts. For this reason, a deliberate effort has been made to minimize the use of nonlinear analysis throughout this investigation. This is accomplished by selectively using nonlinear methods only for those portions of the structure whose behavior is substantially nonlinear.

Nonlinear behavior is largely confined to the composite membrane deck; the remainder of the bridge superstructure can be assumed to behave linearly, under service load conditions. (Nonlinearity in the structure is discussed in Section 2.3.) Thus, nonlinear finite element analysis is used to predict the behavior of the deck. Computed results of these nonlinear studies provide input for linear analyses of the entire bridge superstructure.

Four different finite element models are used-two nonlinear models for the membrane deck and two linear models for the bridge superstructure. For reference, they are designated Membrane Deck Model 1, Membrane Deck Model 2, Bridge Model 1, and Bridge Model 2. The purpose of each model is discussed in Section 1.4.2 below. The models themselves are described in detail in Chapter 3. Both membrane deck models use the computer program ADINA (Automatic Dynamic Incremental Nonlinear Analysis) [1, 2, 3]. The bridge models use the SAP IV linear finite element program [7]. Both programs are run on Lehigh University Computer Center's CDC Cyber-850 mainframe computer.

The use of separate, independent finite element models for analysis of the composite membrane deck dictates that the interaction between the deck and the remainder of the superstructure be carefully considered. Throughout this study, the interface is taken into account in the definition of boundary conditions and applied loads for all four finite element models.

1.4.2 Research Phases

This research is performed in two major phases, which are interrelated and necessarily sequential.

1.4.2.1 Investigation of Composite Membrane Deck Behavior

In the first phase, section properties are defined for the composite membrane deck. The effect of the orientation of Kevlar-49 and E-glass fibers is studied, and an optimum fiber orientation is recommended. Of particular importance in this analysis is a study of the manner in which a transverse load, applied by a vehicle tire, is distributed from its point of application to the deck's supports.

Two supplemental parametric studies are also performed. In the first, the effects of variations in the size and shape of the vehicle tire "footprint" are examined; in the second, the interface between the membrane deck and the remainder of the superstructure is studied.

Membrane Deck Model 1 and Bridge Model 1 are used to perform all research contained in this phase. By design, these two models are fully compatible with each other.

1.4.2.2 Investigation of Bridge Behavior

In the second phase, the global response of the LV/FB to design loads is studied. The optimum membrane fiber orientation selected in the first phase is assumed. The focus of reported results is on stresses and deflections in selected critical structural members. Based on these results, the load capacity of the existing bridge design is evaluated. Recommended design changes are presented for all identified deficiencies.

Membrane Deck Model 2 and Bridge Model 2 are used for this phase. Essentially, they are modified versions of the two models used in the first phase. The modifications permit application of more generalized loading conditions.

1.4.3 Guidelines for Finite Element Modeling

The finite element method provides engineers with a powerful tool for structural analysis; however, finite element analysis is no substitute for good engineering judgement. A finite element model is, by nature, an idealization of the structure it represents. This idealization must necessarily be based on a number of simplifying assumptions, which are often based solely on the judgement of the analyst. The accuracy of computed finite element results is largely dependent on the appropriateness of those assumptions.

The unorthodox design of the LV/FB necessitates several substantial simplifying assumptions. Accordingly, this investigation is characterized by a *cautious approach* to finite element modeling. The following guidelines have been applied, to the greatest extent possible:

(1) All simplifying assumptions are identified for each finite element model.

(2) Simplifying assumptions err on the conservative side, wherever possible.

(3) Where it is not certain whether or not a simplifying assumption is conservative, the impact of the assumption is determined through a parametric study.

(4) Accuracy of all finite element models is verified by independent manual calculations and computer-generated mesh plots.

2. <u>DESCRIPTION OF BRIDGE</u>

2.1 Design Concept

2.1.1 General Configuration and Terminology

The purpose of this section is to provide a description of the general characteristics and components of the LV/FB. All information presented herein has been obtained from design drawings prepared by the project engineers at BRDEC [23]. The information was current, as of 30 March 1988. In all cases, the actual design drawings contain more detail than is required for this report; thus the figures used for reference in this chapter are simplified versions or combinations of several different design drawings.

Because the bridge is of unusual design, the terminology used to describe its structural components is unfamiliar and potentially confusing. For this reason, all terminology applicable to the LV/FB is defined in this section and used consistently throughout the remainder of the report. The first time each term is cited, it is italicized.

The general configuration and overall dimensions of the LV/FB are illustrated in Figure 1. Plan and elevation views are shown, and major structural components are indicated. Longitudinal sections, lettered A through II, are designated as well. These are provided solely for reference in this report. They are used extensively in the presentation of the results of analyses (Chapters 4 and 5).

Note that the LV/FB is composed of two identical halves, connected by a center link assembly. Each half accommodates the tires on one side of a crossing vehicle. The vehicle straddles the open space between the two halves, and its weight is distributed to the two halves approximately evenly. The center link assembly is a collapsible,

spring-loaded mechanism which serves only to ensure correct alignment of the two halves. Its contribution to the lateral and torsional stiffness to the structural system is negligible. Thus the two halves of the bridge are virtually independent of each other, particularly with respect to vertical loads.

Each half of the LV/FB is composed of five modules—a center bay, two ramp bays, and two end ramp bays. Modules are connected together by an arrangement of hinges and latches which permit the bridge to be folded for transportation. Each module is a space frame, constructed of welded aluminum alloy tubular frame members and reinforced with steel diagonal cable braces. The end ramp bays have a solid deck made of aluminum planks; the other three modules have a flexible composite membrane deck, composed of Kevlar-49 and E-glass fibers embedded in a neoprene matrix. (In the figure, the composite membrane deck is shown installed on only one half of the bridge, for clarity.)

The composite membrane deck actually consists of six separate pieces of material, one for each of the center and ramp bays. Each piece is continuously anchored on all four edges—two on the top tubular frame members, and two on the aluminum deck end plates, transverse members which are connected to the top tubular frame members at the ends of each module. The edges of the flexible membrane are wrapped around the frame members and attached with heavy-duty Velcro material Use of Velcro provides a unique, if unorthodox, means of quickly replacing unserviceable deck sections in the field.

Figure 2 shows a typical cross section of the center bay. The figure shows the position of the composite membrane deck and identifies the four basic tubular frame members found throughout the LV/FB superstructure. The top chord and bottom chord members are the principal load carrying elements of the structure. The bottom

chords have the same cross section for the full length of the bridge. The top chords have a tubular cross section only in the center and ramp bays; in the end ramp bays, the tubes are replaced by rectangular box sections. (The configuration of the end ramp bays is detailed in Section 2.2.4.) The continuity of the chords is broken only at the hinges and latches where the modules connect. The chords are 3 inch diameter tubes with wall thickness of 0.125 inch, as shown in Detail A. The vertical members, called *uprights*, are oval-shaped tubes rigidly connected to the top and bottom chords. Detail B shows a typical cross section of an upright. The long axis of the cross section is oriented longitudinally in the bridge. Pairs of uprights are connected together by *cross members*. These sections are 1 inch diameter tubes, as illustrated in Detail C. In the center bay, each pair of uprights is connected by two cross members, as indicated in the figure. Note that the top cross member is positioned well below the level of the top chords, to allow for large deflections of the membrane deck under load. In the ramp bays, the configuration of the cross members varies significantly, because of the decreased depth of the frame at the outer ends of these bays.

The configuration of cross members in a typical ramp bay is shown in Figure 3. Longitudinal sections are as defined in Figure 1. Note that only the innermost four pairs of uprights—Sections H, I, J, and K—have two cross members each. Sections E, F, and G have only one cross member, and Sections C and D have none at all. This configuration is dictated by vertical clearance requirements, to allow for deflection of the composite membrane deck. Because of the reduced number of cross members, the outer ends of the ramp bays are laterally and torsionally less stiff than the remainder of the bridge. This aspect of the superstructure geometry is of particular interest in this study.

2.1.2 Employment

The design concept of the LV/FB is dictated largely by operational requirements and constraints. The most important of these are the requirements for light weight, transportability, and simplicity of operation and maintenance. The extent to which the LV/FB meets these requirements is best illustrated by a brief description of the planned employment of the system in the field.

Figure 4 shows the LV/FB in the travel mode. The bridge is folded, mounted on its trailer, and towed by a HMMWV. The total length of the folded bridge is 166 inches—the length of the center bay. In this mode, the system has little adverse effect on the mobility of the HMMWV. The bridge and trailer weigh less than 3400 pounds. Thus the LV/FB can be quickly transported to bridging sites almost anywhere in an area of operations.

Upon arrival at a bridging site, the LV/FB is manually unfolded by the vehicle's crew, as illustrated in Figure 5. In this figure, the near half of the bridge is depicted as partially unfolded, while the far half is shown completely extended. Note that in the travel mode, both halves of the bridge are stowed sideways, their decks oriented vertically and facing inward. The bridge is unfolded while still in that orientation. First the ramp bays, then the ramp end bays are rotated outward away from the trailer until the bridge halves are fully extended. Individual bays are locked into position by engaging the latches and by inserting shear pins into the hinges. The two halves of the bridge are rotated into their proper horizontal orientation, and the center link assembly is engaged to enforce their alignment. At this time, the bridge is ready to be launched.

Figure 6 shows the launching sequence. Note that the tongue of the trailer is actually a telescoping tube, which must be extended to provide adequate clearance

during the unfolding process. The bridge is mounted on the trailer by means of rollers which surround the inside bottom chords. These rollers permit the bridge to be slid rearward to the launch position, as shown in the figure. Once this is accomplished, the crew launches the bridge by simply driving the HMMWV rearward until the trailer rolls into the gap. When both halves of the LV/FB are bearing fully on both sides of the gap, the bridge is ready for use.

The LV/FB is capable of spanning a 35 foot gap. Prepared abutments are not required, though the ends of the bridge should rest on soil which is relatively firm and level. The load classification of the LV/FB is given as Military Load Class 7 (MLC 7), a capacity of approximately 7 tons. (Military Load Class is discussed in Section 5.2.2.)

2.1.3 Trilateral Code

Design of the Light Vehicle/Foot Bridge is governed by the <u>Trilateral Design</u> and <u>Test Code for Military Bridging and Gap-Crossing Equipment</u>, hereafter referred to as the Trilateral Code [24]. This document is the product of an international agreement to standardize the design of military bridging systems. The participants in the agreement are the Federal Republic of Germany, the United Kingdom, and the United States. Though the Trilateral Code is not directly affiliated with the North Atlantic Treaty Organization (NATO), it does incorporate the provisions of several Standard NATO Agreements (STANAG).

The Trilateral Code is, in fact, a complete design specification. It is generally similar in both concept and content to the American Association of State Highway and Transportation Officials (AASHTO) <u>Standard Specifications for Highway Bridges</u> [5]. Like the AASHTO Specification, the Trilateral Code contains a wide range of provisions governing the design, analysis, and testing of bridges. Provisions which are

pertinent to this research are as follows:

- (1) Definitions of all design loads, to include dead load, vehicle load, impact load, mud load, snow and ice load, wind load, and horizontal braking load
- (2) Formulas for load combinations
- (3) Allowable stresses
- (4) Properties of metallic materials.

The Trilateral Code provides the framework for the analysis of the LV/FB presented in this report. Specific provisions of the code are discussed in detail in Chapters 4 and 5, in the definition of finite element load cases and in the interpretation of computed results.

2.2 Structural Details

2.2.1 Welded Connections

Figure 7 shows the configuration of the welded connections with which the tubular frame members of the LV/FB superstructure are joined. The most important characteristic of these connections is the mechanical interlocking of connected members. In general, wherever two members are joined, the smaller section is inserted through a pair of holes in the larger one. The members are held in position by groove and fillet welds, as shown; however, the rotational stiffness of the connection derives primarily from the geometric arrangement of the intersecting tubes. This arrangement ensures that, under load, these connections will behave in a rigid manner; i.e., the *relative* rotations of connected members will be negligible.

The obvious disadvantage of this connection configuration is the significant loss of section resulting from the large holes in the chords and uprights. For example, the loss of section in the top and bottom chords where they join an upright is approximately 20%. The problem is compounded by stress concentrations and residual weld stresses in the immediate vicinity of the holes. To some degree, loss of section in the connection is offset by the welds themselves, which bind the edges of the holes to the inserted member.

2.2.2 Diagonal Cable Braces

The arrangement of a typical pair of diagonal cable braces is indicated in Figure 8. The braces are used in the center and ramp bays, as shown in Figure 1. They are made of $\frac{1}{8}$ inch diameter steel cable and are mounted to the superstructure with threaded inserts. Each diagonal cable brace has a turnbuckle for tension adjustment.

Steel cable has neither flexural nor compressive stiffness. For this reason, diagonal cable braces are arranged in pairs. Under any given loading condition (with a few unlikely exceptions) only one of each pair of braces is in tension. The other brace is slack, and thus is not active in the structural system.

2.2.3 Hinges and Latches

Sixteen sets of hinges and latches connect the LV/FB's ten modules together—hinges at the bottom chords and latches at the top chords. These components are vital to the successful employment of the bridge, since they permit the structure to be folded for transportation. When the LV/FB is in use, the hinges and latches must transmit substantial loads between connected segments of the bottom and top chords.

Figure 9 shows a typical hinge in both the unfolded and folded positions. The assembly consists of an arrangement of pins, links, and gears, which facilitate rotation of the bottom chord through a full 180 degrees. The main pins are easily removable, to

facilitate replacement of modules. In the unfolded configuration, the two shear pins lock the gears into position. When the bridge is loaded, the hinges transmit both axial tension and shear between the connected chords. However, even with the shear pins in place, some free rotation of the assembly is possible. Thus no flexural stiffness is attributed to the hinges.

A cutaway view of a typical latch is shown in Figure 10. The end plates are welded to both chord segments. These plates provide a bearing surface for the large compressive forces in the top chord. The acorn nut functions as a shear key. The spring-loaded catch holds the entire assembly in proper alignment, but is really not required for transmission of loads.

2.2.4 End Ramp Bays

The configuration of a typical end ramp bay is detailed in Figure 11. The construction of this module is significantly different than that of the center and ramp bays. It has only one cross member, a 3 inch diameter tube which is welded to the bottom chord members at the base of the ramp. At the top chords, short stubs of 3 inch tubing provide continuity with the adjacent ramp bay and mount the female ends of the latches. The uprights and the remainder of the top chords are constructed of rectangular box sections with dimensions as indicated in Detail A. The deep rectangular section is used to increase the shear capacity of this portion of the bridge. in the vicinity of the supports, where shear forces are expected to be large. Unlike the other modules, the end ramp bay has a solid deck. It consists of ten commercially manufactured aluminum planks, which are welded to the top chord members.

Twelve deck end plates are used in the LV/FB superstructure. They are mounted on the center and ramp modules to anchor the ends of the composite membrane deck, as shown in Figure 1. They are fabricated from $\frac{1}{16}$ inch thick aluminum sheet and covered with Velcro fabric, which is used to attach the membrane.

2.3 Material Properties

2.3.1 Aluminum

The aluminum alloy used for the tubular frame members in the LV/FB superstructure is Aluminum 7005. Its significant alloying elements are as follows [24]:

> Silicon (Si) -0.35%Iron (Fe) -0.40%Copper (Cu) -0.10%Manganese (Mn) -0.20-0.70%Magnesium (Mg) -1.0-1.8%Chromium (Cr) -0.06-0.20%Zinc (Zn) -4.0-5.0%Titanium (Ti) -0.01-0.06%

The modulus of elasticity and shear modulus of Aluminum 7005 are given as 71×10^3 N/mm² (10295 ksi) and 27 x 10^3 N/mm² (3915 ksi), respectively. Its yield stress, defined as 0.2 percent strain, is 310 N/mm² (44.95 ksi), and its density is 2800 kg/m³ (0.10116 pounds/inch³) [24].

The stress-strain relationship for a typical aluminum alloy is shown in Figure 12 [4]. Yield stress and allowable stress are indicated. The Trilateral Code defines allowable stress as $\frac{\text{Yield Stress}}{1.33}$, the magnitude of which is indicated on the figure. The nature of the curve below the allowable stress level suggests that the behavior of an aluminum alloy can be assumed to be approximately linear within that range.

The only steel structural components in the LV/FB design are the diagonal cable braces. Properties of steel cable are not provided in the Trilateral Code. For this study, the modulus of elasticity of steel is assumed to be 29000 ksi and the material is assumed to behave linearly. Yield stress and ultimate strength are not considered, because steel cable is available with tensile strength far exceeding the requirements of the LV/FB.

2.3.3 Composite Membrane

The exact characteristics of the composite membrane which will form the deck of the LV/FB have not yet been fully defined; however, it is the intent of the LV/FB's designers that the membrane consist of laminae of Kevlar-49 and E-glass fibers encased in a matrix of neoprene (synthetic rubber). The fibers are to be oriented such that the load distribution properties of the composite membrane deck are optimal. There are, of course, infinitely many possible fiber orientations which might be considered. BRDEC has indicated that a simple arrangement of layers oriented at 0°, 45°, and 90° to the bridge's longitudinal centerline is most desirable, to minimize fabrication cost.

Four specific fiber configurations have been considered in this study. They are illustrated in Figures 13, 14, 15, and 16 and defined as follows:

- MEMBRANE A: 50% of Kevlar-49 fibers and 50% of E-glass fibers are oriented at 0° to the longitudinal centerline; 50% of Kevlar-49 fibers and 50% of E-glass fibers are oriented at 90° to the longitudinal centerline (Figure 13).
- (2) MEMBRANE B: 50% of Kevlar-49 fibers and 50% of E-glass fibers are oriented at +45° to the longitudinal centerline; 50% of Kevlar-49 fibers and

50% of E-glass fibers are oriented at -45° to the longitudinal centerline (Figure 14).

- (3) MEMBRANE C: 50% of Kevlar-49 fibers are oriented at 0° and 50% are at 90°; 50% of E-glass fibers are oriented at +45° and 50% are at -45° (Figure 15).
- (4) MEMBRANE D: 50% of E-glass fibers are oriented at 0° and 50% are at 90°; 50% of Kevlar-49 fibers are oriented at +45° and 50% are at -45° (Figure 16).

The use of Kevlar-49 and E-glass fiber reinforcement in composite materials is standard practice; however, these fibers are normally embedded in a relatively stiff matrix of resin or plastic [14]; the use of a flexible neoprene matrix is quite unorthodox. Thus, while the properties of the individual components-Kevlar, glass, and neoprene-have been extensively documented, the elastic properties of laminates composed of these materials are not well understood. Development of new theory for the analysis of composite materials is beyond the scope of the research presented in this report. To analyze the composite membrane deck of the LV/FB, existing laminate theory is applied, to the greatest extent possible. Aspects of the behavior of a neoprene matrix composite which cannot be described by existing theory are handled through the judicious use of assumptions.

2.3.3.1 Fiber Properties

The elastic properties of Kevlar-49 and E-glass fibers are as follows [25]:

	Modulus of Elasticity	r, E Ultimate Stress, σ_u	Ultimate Strain, ϵ_{u}
Kevlar-49	16500 ksi	460 ksi	2.8%
E-glass	10500 ksi	500 ksi	4.8%

These are properties are based on tension tests of individual fibers. Theoretically, the compressive properties are similar, though compression testing of fibers is not practical. The diameter of a fiber of either material is on the order of 0.0005 inch; individual fibers of significant (testable) length cannot carry compressive loads without buckling.

The stress-strain relationship of both materials is virtually linear through the entire range of fiber stress from zero to σ_u . Failure occurs abruptly, particularly for E-glass, which is quite brittle [14].

The above properties are representative values. Test data show considerable scatter in all three measured quantities. This variability in material properties is largely due to the lack of ductility in the material. When a fiber is loaded, stress concentrations develop in the vicinity of minute flaws which occur during manufacture and handling; these stresses cannot be effectively redistributed by local yielding, and eventually brittle fracture occurs. The size and frequency of these flaws are randomly distributed, and fiber properties vary accordingly [14].

Though these properties are best regarded as approximate, they provide vital input for analysis of the composite membrane deck of the LV/FB. Comparison of the elastic properties of the two fiber types yields a simple but important conclusion: Of the two fibers, Kevlar-49 is considerably stiffer, while E-glass has a greater capacity for elastic elongation. This relationship has considerable impact on the efficient utilization of both fiber types in the design of the membrane.

2.3.3.2 Matrix Properties

The stress-strain relationship for rubber is shown in Figure 17 [22]. Because the curve is highly nonlinear, there is no single, well-defined modulus of elasticity. Ultimate strength of neoprene is approximately 3 ksi, and elongation at failure is on the order of 800% [9]. When considering the composite material, however, strain compatibility between the fibers and matrix is assumed. Thus neoprene strains larger than ϵ_u for either Kevlar-49 or E-glass are not of interest. In this analysis, the significant aspect of the stress-strain relationship for neoprene is the tangent modulus of the curve for strains less than 2.8%. In this region of the stress-strain curve, the tangent modulus is much smaller—by a factor of at least 10^{-4} —than the moduli of elasticity for both Kevlar-49 and E-glass.

2.3.3.3 Elastic Properties of Unidirectional Laminae

A unidirectional lamina is a single layer of fiber-reinforced material with uniform thickness, with all fibers parallel and of the same material. In composite materials, unidirectional laminae are combined at different orientations to form *laminates*. Using the "mechanics of materials approach", the elastic properties of unidirectional laminae can be described as simple functions of the properties of the fibers and matrix material. Similarly the elastic behavior of laminates can be described in terms of the elastic properties of individual laminae.

Figure 18 shows an idealized unidirectional lamina [14]. The 1- and 2-directions are defined as parallel and perpendicular, respectively, to the fiber orientation, in the plane of the lamina. The 3-direction is perpendicular to the plane of the lamina. When a uniform in-plane load is applied to the lamina, the strain in the fibers is assumed to be equal to the strain in the matrix. If both materials behave elastically, then the modulus of elasticity of the lamina in the 1-direction, E_1 , is given as

$$E_1 = E_f V_f + E_m (1 - V_f) , \qquad (2.1)$$

and the modulus of elasticity of the lamina in the 2-direction, E_2 , is given as

$$E_2 = \frac{E_f E_m}{E_f (1 - V_f) + E_m V_f} , \qquad (2.2)$$

where

 E_{f} = modulus of elasticity of the fiber material

 $E_{\rm m}$ = modulus of elasticity of the matrix material

 $V_{\rm f}$ = volume fraction = $A_{\rm f}/A$

 A_{f} = total cross sectional area of the fibers

A = total cross sectional area of lamina [14].

Consider now a unidirectional lamina composed of a neoprene matrix and either Kevlar-49 or E-glass fibers. In this case $E_m \ll E_f$, and Equations 2.1 and 2.2 can be reduced to

$$E_1 \approx E_f V_f$$
, (2.3)

and

$$E_2 \approx 0. \qquad (2.4)$$

Equation 2.3 can be rewritten as

$$E_1 A \approx E_f A_f . \tag{2.5}$$

This relationship suggests that the in-plane tensile stiffness of a unidirectional lamina with $E_m \ll E_f$ can be expressed solely in terms of fiber properties. The contribution of the matrix is virtually negligible.

The same unidirectional lamina, subjected to in-plane shear loading, is shown in Figure 19. Note that there is no axial strain in the fibers, regardless of the magnitude of the shear strain, γ . Thus the shear modulus, G, of the lamina is assumed to be equal to the shear modulus of the matrix alone.

The shear modulus of neoprene is not well defined, due to the material's nonlinear behavior. It is known that Poisson's Ratio, ν , is approximately 0.5; and from elementary mechanics of materials, G is given as

$$G = \frac{E}{2(1+\nu)} .$$
(2.6)

Thus, for neoprene, $G \approx E/3$. E is not a constant, as indicated in Section 2.3.3.2; however, for this investigation, it is sufficient to recognize that the shear modulus and the elastic modulus of neoprene are of the same order of magnitude, and that they are both much smaller than the elastic moduli of Kevlar-49 and E-glass.

2.3.3.4 Elastic Properties of the Membrane

A membrane is, by definition, a thin material with negligible flexural stiffness. Stresses are assumed to be constant through the thickness of the membrane; they act in directions that are tangent to the membrane at every point [9].

The membrane which forms the deck of the LV/FB is assumed to satisfy this definition. While specific section properties have not yet been finalized, the thickness of the membrane is expected to be approximately 0.1 inch. As a result, the material is also assumed to have negligible in-plane compressive stiffness. Any significant compressive forces will cause local buckling, in the form of wrinkles, in the deck.

The membrane is composed of layers of unidirectional laminae, the orientations of which are to be determined in this research. Based on the relationships developed in Section 2.3.3.3, each of these laminae is assumed to have in-plane tensile stiffness only in the direction parallel to the fibers. Elastic properties of the *entire laminate* are far more complex and are subject to substantial variations, as the orientations of the laminae are varied. In this investigation, no attempt is made to directly define these properties. Rather, the general approach taken in developing finite element models of the LV/FB's deck is to separately define the individual laminae and their relatively simple elastic properties. Laminae are "bonded" together through the connectivity of finite elements, and the elastic behavior of the entire laminate is then computed in the finite element analyses.
2.3.3.5 Nonlinearity in the Membrane

There are two types of nonlinearity in structures and structural components-material nonlinearity and geometric nonlinearity [16]. Material nonlinearity is exhibited by structural materials for which Hooke's Law is not valid. Geometrical nonlinearity is exhibited by structures which undergo large displacements. A "large displacement" is one which is significant enough to affect the equations of static equilibrium for the structure. The composite membrane deck of the LV/FB exhibits both types on nonlinearity.

The material behavior of the individual laminae which constitute the membrane is actually quite linear under tensile loading. Nonetheless, significant material nonlinearity is present simply by virtue of the membrane's complete lack of compressive stiffness.

Geometric nonlinearity in the composite membrane deck is a result of the material's lack of flexural stiffness. In response to transverse (out-of-plane) loads, the membrane can only develop in-plane stresses. For this reason, the deck must undergo large displacements.

This sort of geometrically nonlinear behavior is exhibited by the simple twomember truss shown in Figure 20. In the undeflected position, the structure is geometrically unstable. There is no resistance to incipient rigid body rotation of the two members about their supports. Thus, like the composite membrane deck of the LV/FB, this structure has no flexural stiffness. In response to a transverse load, *P*, the members can only develop axial bar forces. When loaded, the structure does not attain geometric stability until it undergoes a substantial vertical deflection. The final deflected position is such that the applied load is balanced by the sum of the vertical components of the two axial bar forces. Compatible axial elongation of the members

must also occur. In effect, static equilibrium cannot be achieved until a large displacement takes place.

The geometrically nonlinear behavior exhibited by the composite membrane deck is illustrated in Figure 21. A section of the deck, supported on all four edges and subjected to a vertical tire load, is shown in the undeflected and deflected positions. Again, the structure attains geometric stability only after undergoing a large vertical deflection. Equilibrium can only be satisfied in the deflected position. This behavior is fundamentally the same as that of the two-member truss, except that the composite membrane deck is a three dimensional structure with infinitely many degrees of freedom.

Geometric nonlinearity requires a second-order analysis—one in which the final equilibrium state is computed with the applied loads in their displaced positions. Such an analysis can be performed satisfactorily using nonlinear finite element methods.

2.4 Critical Members

One of the principal objectives of this investigation, as defined in Section 1.3. ... to evaluate the adequacy of certain critical members of the LV/FB superstructure. Specifically, those critical members are:

- (1) the top chords in the center and ramp bays, and
- (2) the uprights.

The top chords are of particular interest because they are subjected to a highly complex combination of local and global loads. They carry large compressive axial forces and somewhat smaller bending moments due to the global bending of the bridge they also carry substantial local axial forces, shear forces, bending moments, and torsion, due to vehicular loads transmitted circumferentially to the chords by the composite membrane deck.

Designation of these members as "critical" is based largely on the expressed needs of the project engineers at BRDEC. Discretization of finite element models, development of finite element load cases, and presentation of results are all focused primarily on these elements of the bridge superstructure. Other members are discussed, but not in the same degree of detail.

3. DESCRIPTION OF FINITE ELEMENT MODELS

3.1 Finite Element Analysis Computer Programs

3.1.1 The Finite Element Method

The fundamental concept of the finite element method is that the continuum properties of a structural system can be idealized as an assemblage of discrete elements, which are interconnected at nodal points. The behavior of these finite elements is governed by assumed functions describing their displacements or stresses [10]. Both SAP IV and ADINA, the finite element analysis computer programs used in this study, are based on a *stiffness formulation*. In this formulation, the mechanical properties of each finite element are represented in an element stiffness matrix, which relates forces and displacements at nodal points. During problem solution, user-supplied geometric and material properties are used to formulate the element stiffness matrices. These are then assembled into a global stiffness matrix, which forms a system of linear simultaneous equations relating known (user-supplied) nodal loads to unknown nodal displacements. The system of equations is solved, and the computed nodal displacements are subsequently used to determine all element stress resultants.

A detailed description of finite element theory is beyond the scope of this report. The method is documented in published sources too numerous to cite. Theory presented in Reference 6 is particularly pertinent to this study, because the author, Bathe, is one of the developers of both SAP IV and ADINA.

Though finite element theory is not discussed in this report, certain specific aspects of the two finite element programs are particularly pertinent to the analysis of the LV/FB. These features significantly influence the configuration of the four finite element models.

3.1.2 SAP IV

SAP IV is a conventional linear finite element analysis program. Small displacements and linear elastic material behavior are assumed. The program is capable of performing both static and dynamic analyses, though only static analyses are used in this study. SAP IV has no pre- or postprocessing capability. Mesh geometry, boundary conditions, element properties, material properties, and loads are defined via fixed-format input data file. A simple graphics program, called SPLT, is available for producing finite element mesh plots for model verification [15].

Specific aspects of SAP IV which are of particular interest in this study are as follows [7]:

(1) Translational and rotational degrees of freedom must be explicitly defined for each nodal point. Structural boundary conditions are defined by suppressing the appropriate degrees of freedom at each support.

(2) The program has no capability to renumber nodal points, for the purpose of minimizing the bandwidth of the global stiffness matrix. Thus node numbering is of critical importance in ensuring computational efficiency.

(3) If required, the program can automatically compute member self-weights and apply them to the structural model as equivalent nodal loads.

(4) Continuity of connected beam members can be modified through the use of member end releases. When an end release is specified, the corresponding force or moment component is equal to zero.

3.1.3 ADINA

ADINA is a sophisticated finite element program, which is capable of performing

three levels of nonlinear structural analysis [6]:

- (1) Structures which are materially nonlinear only. (Stress-strain relationship is nonlinear.)
- (2) Structures which undergo large displacements, but small strains. (Stress strain relationship may be linear or nonlinear.)
- (3) Structures which undergo large displacements and large strains. (Stressstrain relationship may be linear or nonlinear.)

All nonlinear analyses of the LV/FB's composite membrane deck are in category (2). The nature of this nonlinearity is discussed in Section 2.3.3.5.

In general, ADINA evaluates the nonlinear response of a structural system by performing an incremental solution of the equations of equilibrium. Only one load case can be analyzed in a single computer run. Loads are applied in steps, according to a user-defined load function. At specified load steps, the global stiffness matrix is updated to account for changes in the stiffness of the structure as it deforms. Also at specified load steps, equilibrium iterations are performed to ensure that equilibrium is satisfied in the deformed position at all nodal points [3].

The version of ADINA used in this study has no preprocessing capability. As with SAP IV, the finite element model is defined via fixed-format input data file. A postprocessor, called ADINA Plot, is available for producing graphical output [2].

Specific aspects of ADINA which are of particular interest in this investigation are as follows [1]:

(1) Definition of nodal degrees of freedom and structural boundary conditions is performed in the same manner as in SAP IV.

(2) For each element type, a linear formulation and several different nonlinear

formulations are available. The Updated Lagrangian formulation is consistent with the nature of nonlinearity exhibited by the composite membrane deck of the LV/FB.

(3) Linear and nonlinear element formulations can be used in the same finite element model, provided they are defined as separate element groups. For successful execution of a nonlinear analysis, it is essential that the user-defined load function be tailored to the expected response of the structure. Relatively small load steps must be specified for load levels at which large displacements occur. If excessively large displacements occur during a single load step, the equilibrium iteration process may fail.

(5) It is possible to compute a full set of finite element results at each load step. Using this option, a detailed load-deflection history can be obtained from a single load case.

3.2 Membrane Deck Model 1

3.2.1 Purpose

Membrane Deck Model 1 is used for two principal purposes:

- (1) To establish section properties for the composite membrane deck.
- (2) To determine the effects of different fiber orientations on the behavior of the membrane.

These analyses form the basis for selection of an optimum fiber orientation. Note that this model is not used to investigate the behavior of the membrane as a component of the LV/FB structural system; rather, it is used only to evaluate membrane material properties.

3.2.2 Discretization

The portion of the composite membrane deck represented by Membrane Deck Model 1 is shown in Figure 22. The figure is a plan view of the entire bridge; the modeled portion of the deck is shaded. Membrane Deck Model 1 represents of one quarter of the deck segment which covers one center bay of the LV/FB. The model takes advantage of two axes of symmetry. Boundary conditions on these axes are defined such that the behavior of the remaining three quarters of the deck segment is taken into account. Use of axes of symmetry in modeling is described in Reference 18. This technique significantly improves the efficiency of the finite element analysis of the membrane. Its obvious disadvantage is that the loading conditions must also be symmetrical about both axes. This limitation is of no consequence here, however, because Membrane Deck Model 1 is used only to analyze material behavior. Analysis of the composite membrane deck under more realistic loading conditions is performed with Membrane Deck Model 2.

An isometric view of the ADINA finite element discretization of Membrane Deck Model 1 is shown in Figure 23. The figure is a mesh plot produced by the ADINA Plot postprocessing program. The orientations of the global x-, y-, and z-axes are indicated. In the model, the membrane is represented by a planar arrangement of nonlinear truss/cable elements. Each element represents a well-defined quantity of parallel Kevlar-49 or E-glass fibers in a unidirectional lamina. In effect, the continuum properties of a lamina are "lumped" into a series of regularly spaced line elements. This technique is analogous to the use of a "gridwork" of beam elements to model the bending behavior of a plate, as described by Hrennikoff in Reference 13. The significant difference in this application is that, unlike a plate, the composite membrane deck has no virtually no flexural stiffness. For this reason, truss/cable elements are used in the membrane model. They are oriented at 0°, 45°, and 90° to the longitudinal centerline, just as the Kevlar-49 and E-glass fibers in the membrane are.

Membrane Deck Model 1 has 513 active degrees of freedom. The nodal points at which the truss/cable elements are interconnected are free to translate in all three global directions. Rotational degrees of freedom are not defined, because truss/cable elements have no flexural stiffness properties. Note that this arrangement would not be possible in a linear finite element analysis. A plane truss with out-of-plane translational degrees of freedom would be geometrically unstable; zero values would occur on the diagonal of the stiffness matrix, and solution of the system of simultaneous equations would be impossible. The configuration used in Membrane Deck Model 1 is possible only because of the nonlinear formulation of the ADINA truss/cable element. In this formulation, provision is made for application of an initial axial strain to the element. If the initial strain is tensile, out-of-plane loading and displacements of the structure are possible.

This capability is unique to nonlinear finite element analysis. In a conventional, linear formulation, a truss element has only axial stiffness. All terms in the element stiffness matrix associated with lateral degrees of freedom are zero. In the Updated Lagrangian formulation of the ADINA nonlinear truss/cable element, application of an initial tensile strain causes lateral stiffness to be assigned to the element. As a result, the assembled global stiffness matrix for Membrane Deck Model 1 is nonsingular. The plane truss does have out-of-plane stiffness and can resist out-of-plane loads, provided that the first few load steps are very small. As out-of-plane displacement progresses, the entire structure stiffens, and load steps can be progressively increased. The actual load functions used for various analyses are described in Chapter 4.

Based on the relationships developed in Section 2.3.3.3, the stiffness of the

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neoprene matrix is not considered in the discretization of Membrane Deck Model 1. It is assumed that the neoprene's sole contribution to the behavior of the composite membrane deck is to maintain the alignment and relative positions of the reinforcing fibers. This contribution is modeled through the connectivity of truss members at nodal points in the finite element model.

Figure 23 also illustrates the use of boundary elements along two edges of Membrane Model 1. These elements simulate the support provided to the composite membrane deck by the bridge superstructure. They are discussed in Section 3.2.4.

For all analyses of membrane load distribution properties, Membrane Deck Model 1 is loaded with a single vehicle tire load. The load is represented as a series of concentrated loads, applied to the nodal points near the center of the membrane deck. (The center of the membrane deck is the *corner* of the finite element model, where the two axes of symmetry intersect.) The appropriate vehicle tire load is specified in the Trilateral Code and is described in detail in Section 4.1.2.

3.2.3 Nonlinear Truss/Cable Elements

In Membrane Deck Model 1, all truss/cable elements which represent longitudinal (x-direction) and transverse (y-direction) fibers are exactly 3 inches long. Those oriented diagonally are 4.242 inches long. A regular, square mesh is required, so that material properties of the elements can be defined consistently throughout the finite element model.

Four different configurations of Kevlar-49 and E-glass fibers are considered in this study, as defined in Section 2.3.3. As a result, four different sets of material properties for the nonlinear truss/cable elements are used. In general, definition of material properties is performed in the following manner:

(1) All elements are assigned a compressive stiffness of zero. In ADINA, this is accomplished by defining a "nonlinear elastic" stress-strain relationship.

(2) The tensile modulus of elasticity assigned to a given truss/cable element is equal to the modulus of elasticity of the type of fiber that element represents. In those cases where Kevlar-49 and E-glass fibers are oriented in the same direction (MEMBRANES A and B), the average of the two moduli is used. This procedure is appropriate, provided that the amounts (cross sectional areas) of Kevlar-49 and E-glass represented by a single element are equal.

(3) The cross sectional area assigned to a given truss/cable element is equal to the total cross sectional area of all fibers contained within a tributary area, as shown in Figure 24. Note that the tributary area for diagonal elements is smaller, by a factor of $\frac{1}{\sqrt{2}}$, than the area for longitudinal and transverse elements. The cross sectional areas of elements which lie on the axes of symmetry are reduced by 50%.

(4) For MEMBRANES A and B, there are no fibers at all in two of four directions. Absence of fibers in a given direction is modeled by assigning a very small modulus of elasticity to the appropriate truss/cable elements. This procedure is considerably simpler than physically removing these elements from the finite element mesh.

To ensure that the finite element model is geometrically stable with respect to out-of-plane displacements, initial tensile strain must be specified for all truss/cable elements which represent composite fibers. For all analyses involving Membrane Deca Model 1, initial strains are computed on the basis of a one pound tensile force applied to each element. The result is a small, uniform prestress in the membrane, which is consistent with the initial stretching of the actual composite membrane deck as it is installed on the LV/FB superstructure. Furthermore, the initial prestress is very small.

compared to the computed fiber stresses in the loaded membrane, which exceed 100 ksi in all analyses.

3.2.4 Boundary Conditions

Two edges of Membrane Deck Model 1 are supported. These edges represent the attachment of the composite membrane deck to the bridge superstructure. The edge nodal points are restrained, not by suppressed degrees of freedom, but by boundary elements oriented in the three global directions, as shown in Figure 23. The boundary elements are linear truss elements with very large axial stiffness, such that they approximate rigid supports. When a load is applied to the membrane, the computed forces in these elements provide a direct measure of the distribution of loads to the top chords of the bridge. In this study, computed forces in boundary elements are referred to as membrane boundary forces.

The other two edges of the model are unsupported. They represent the two axes of symmetry, specified such that the portion of the membrane not modeled is taken into account in the analysis. For all nodal points on the longitudinal axis of symmetry. the transverse (y-direction) translational degree of freedom is suppressed. For all nodal points on the transverse axis of symmetry, the longitudinal (x-direction) translational degree of freedom is suppressed.

3.2.5 Assumptions

The significant assumptions incorporated into the formulation of Membrane Deck Model 1 are summarized as follows:

(1) The membrane has no flexural or compressive stiffness.

(2) The tensile properties of Kevlar-49 and E-glass fibers in unidirectional laminae can be lumped into a series of parallel, equally spaced truss/cable elements.

(3) The only contribution of the neoprene matrix to the behavior of the membrane is to maintain the position and alignment of the reinforcing fibers.

(4) Prior to loading, the composite membrane deck has a small tensile prestress, due to stretching during installation. Implicitly, then, it is also assumed that there is no initial slack in the membrane.

(5) The top chords of the LV/FB provide rigid support to the membrane. They do not displace as the membrane is loaded.

(6) The Velcro connection of the composite membrane deck to the top chords does not slip when the membrane is loaded.

(7) A vehicle tire load can be represented as a series of equivalent concentrated loads, applied to nodal points in the finite element model.

Of these assumptions, (5) and (7) are most questionable (and most likely to be unconservative). The top chords of the bridge actually undergo substantial displacements under load; and the size, shape, and distribution of a vehicle tire load applied to the flexible membrane is potentially quite complex. Thus assumptions (5) and (7) are verified through the use of parametric studies. These studies are described in Sections 4.3 and 4.4.

3.3 Bridge Model 1

3.3.1 Purpose

Bridge Model 1 is used in conjunction with Membrane Deck Model 1 to study

the behavior of the composite membrane deck. Specific purposes of the model are as follows:

(1) Bridge Model 1 is used to provide a basis for comparison of alternative membrane fiber orientations. For the four alternative membrane configurations, stresses generated in the top chord of the bridge are computed and compared.

(2) The model is used in a parametric study of the effect of top chord displacements on the behavior of the composite membrane deck.

Membrane Deck Model 1 and Bridge Model 1 are fully compatible. For each nodal point on the supported edge of the membrane model, there is a corresponding nodal point on the top chord of the bridge model. Computed forces in the boundary elements of the membrane model can be applied directly to the bridge model as concentrated loads, without modification. Because it is only compatible with Membrane Deck Model 1, Bridge Model 1 is not used to investigate the behavior of the LV/FB under realistic loading conditions; rather, it is used only to facilitate the evaluation of membrane material properties.

3.3.2 Discretization

An isometric view of the SAP IV finite element discretization of Bridge Model 1 is shown in Figure 25. The figure is a mesh plot produced by the SPLT computer program. The orientations of the global x-, y-, and z-axes are indicated. Because the two halves of the LV/FB are virtually independent of each other, only one half of the structure is represented in the finite element discretization. The model has 412 nodal points. In general, they are located at the welded connections of tubular frame members and at the hinges and latches. In the top chord of the center bay, additional nodal points and members have been provided at 3 inch intervals, to ensure

compatibility with Membrane Deck Model 1. Except for the supports, all nodal points have six degrees of freedom—three translational and three rotational. The model has a total of 2425 active degrees of freedom.

3.3.3 Tubular Frame Members

Because the LV/FB superstructure is in fact a space frame, all tubular frame members are modeled with beam elements. Dimensions, section properties, and material properties are as described in Chapter 2. In modeling the top chord, special provision is made for the fact that the composite membrane deck is attached to the top edge-not the centroidal axis-of the tubular member.

Figure 26 shows the finite element representation of a typical segment of a top chord. Note that $1\frac{1}{2}$ inch long vertical beam elements are added to the top chord beam elements at 3 inch intervals. They represent the actual radius of the top chords. Membrane boundary forces, computed with Membrane Deck Model 1, are applied to the nodal points at the tops of these elements, as shown. Because the radius of the top chord remains virtually constant under load, the $1\frac{1}{2}$ inch elements are defined as being virtually rigid. Their cross sectional area, flexural inertia, and modulus of elasticity are very large, with respect to those of the top chord.

3.3.4 Diagonal Cable Braces

All diagonal cable braces are modeled with truss elements. Provision is made for the fact that normally only one of each pair of braces is in tension for a given loading condition. The other is slack and does not contribute to the structural response. In Bridge Model 1, the slack cable in each pair is "removed" from the finite element mesh by assigning it a very low modulus of elasticity. Of course, this technique dictates that

two separate finite element analyses be performed for each load case—one to identify all slack cables and one to analyze the structural response with the slack cables removed.

The diagonal cable braces are assumed to be made entirely of steel cable. The existence of turnbuckles and threaded inserts is ignored. The cables are assumed to have no tension when the bridge is in the unloaded condition.

3.3.5 Hinges and Latches

Hinges and Latches are modeled through the use of member end releases. In each case, end releases are specified for the particular beam element which terminates at the location of the hinge or latch. Each hinge is represented by the release of the moment component in the global y-direction. Each latch is represented by the release of all three moment components.

3.3.6 Node Numbering

Figure 27 shows the node numbering scheme used in Bridge Model 1. A typical section of the center bay is shown, with nodal points and node numbers indicated. In general, nodes are numbered first in the global z-direction, then in the y-direction, and finally in the x-direction. Through this scheme, the bandwidth of the 2425×2425 global stiffness matrix is kept to 177.

3.3.7 Boundary Conditions

Because the deployed LV/FB does not rest on prepared bearings or abutments. definition of appropriate structural boundary conditions is a subjective matter. The approach taken here is to assume conditions of minimal restraint at the supports. In general, this represents a worst case assumption.

Figure 28 illustrates the structural boundary conditions used in all analyses involving Bridge Model 1. Suppressed degrees of freedom (reactions) are indicated. Only the four extreme corners of the bridge are supported. These corners are restrained from vertical (z-direction) translation, but have only enough lateral restraint to prevent rigid body rotation of the entire structure.

3.3.8 Assumptions

The significant assumptions incorporated into the formulation of Bridge Model 1 are summarized as follows:

(1) The behavior of all aluminum and steel components is linear elastic. All displacements are small.

(2) The two halves of the LV/FB are virtually independent of each other. The center link assembly, which connects them, does not affect the structural response of either half.

(3) All welded connections of tubular frame members are fully rigid.

(4) Loss of section at welded connections does not affect the global behavior of the structure.

(5) Diagonal cable braces are made entirely of steel cable. They have no strength in compression and no flexural stiffness.

(6) Hinges are capable of carrying axial load, shear in both directions, torsion. and bending moment in the global z-direction only.

(7) Latches are capable of carrying axial load and shear in both directions, but

no torsion or bending moment.

(8) No differential settlement of the corners of the bridge occurs under load.

3.4 Membrane Deck Model 2

3.4.1 Purpose

Membrane Deck Model 2 is used in conjunction with Bridge Model 2 to analyze the structural response of the LV/FB to design loads. Its principal purpose is to determine, for a given set of loads applied to the composite membrane deck, what corresponding loads are transmitted to the bridge superstructure. Thus the configuration of Membrane Deck Model 2 is primarily oriented toward analyzing the contribution of the membrane to the global behavior of the entire LV/FB structural system.

3.4.2 Discretization

The portion of the composite membrane deck represented by Membrane Deck Model 2 is shown in Figure 29. The figure is a plan view of the entire bridge; the modeled portion of the deck is shaded. Membrane Deck Model 2 represents the composite membrane deck segments which cover one center bay and one ramp bay of the LV/FB. Because all deck segments are physically separated from each other, it is only necessary to include one ramp bay in the finite element discretization. Unlike Membrane Deck Model 1, axes of symmetry are not considered. In general, design loads are longitudinally and transversely asymmetrical; wind load and longitudinal braking force, for example, are normally asymmetrical.

An isometric view of the ADINA finite element discretization of Membrane Deck Model 2 is shown in Figure 30. The figure is a mesh plot produced by ADINA Plot. Note that the portion of the model which represents the ramp bay deck is inclined at the angle of the top chord. Despite the obvious geometric differences, the fundamental concept of the discretization is identical to that of Membrane Deck Model 1. The membrane segments are modeled by a planar arrangement of nonlinear truss/cable elements, which represent the Kevlar-49 and E-glass fibers in a series of unidirectional laminae. Elements are assigned a small initial strain, such that stable, out-of-plane displacement can occur under load. The contribution of the neoprene matrix to membrane stiffness is neglected. In general, the only significant differences between the two models are the size of the mesh and the treatment of the membrane boundaries.

Because Membrane Deck Model 2 necessarily includes a larger portion of the composite membrane deck, the mesh is composed of a 6 inch grid, rather than the 3 inch grid used in Model 1. At element level, cross sectional area and initial strain are modified to account for the difference. The coarser mesh is justified by the fact that Model 2 is only used in applications which do not require detailed information about the behavior of the membrane itself. Despite the coarser mesh, this discretization has 819 active degrees of freedom, 60% more than Model 1.

Because Membrane Model 2 is subjected to realistic, asymmetrical loading conditions, boundary elements are used along both sides of the membrane. Their orientation and properties are identical to those of the boundary elements used in Membrane Deck Model 1. Unlike Model 1, however, boundary elements are not used on the transverse edges; rather, beam elements are used to more accurately represent the deck end plates which support the ends of the composite membrane deck segments.

Membrane Deck Model 2 is loaded with the appropriate design loads specified in the Trilateral Code. These are discussed in detail in Section 5.2.

The significant assumptions used in formulating Membrane Deck Model 2 are

identical to those specified for Model 1 in Section 3.2.5.

3.5 Bridge Model 2

3.5.1 Purpose

Bridge Model 2 is used to analyze the structural response of the LV/FB under design loads. It is fully compatible with Membrane Deck Model 2.

3.5.2 Discretization

An isometric view of the SAP IV finite element discretization of Bridge Model 2 is shown in Figure 31. The figure is a mesh plot produced by the SPLT program. The model is identical to Bridge Model 1, except for minor differences in the top chords, end ramp bays, and structural boundary conditions. Because of these changes, it has 2436 active degrees of freedom, versus 2425 for Model 1.

In Bridge Model 2, the $1\frac{1}{2}$ inch vertical beam elements which represent the radius of the top chord members are spaced at 6 inch intervals, for compatibility with Membrane Deck Model 2. They are provided in the ramp bays, as well as in the center bay. The material and section properties of these elements are identical to those in Bridge Model 1.

The aluminum deck in the end ramp bays is included in Bridge Model 2. A single plate bending element (with membrane stiffness) is used to represent the assemblage of aluminum deck planks in each end ramp bay. While this representation is quite coarse, a higher level of refinement is not justified in this study. The behavior of the aluminum deck planks—and of the end ramp bays themselves, for that matter—is not of interest in this analysis. Only the contribution of these elements to the global behavior of the LV/FB is significant. For that reason, their material

properties are defined such that their self-weight is accurately represented, and their stiffness is conservatively low.

Figure 32 illustrates the structural boundary conditions used in all analyses involving Bridge Model 2. As is the case in Model 1, the bridge is assumed to be supported only on its four extreme corners, and all four corners are constrained against vertical (z-direction) translation. The lateral constraints have been modified, however, for consistency with applied lateral loads. The Trilateral Code specifies both wind load and longitudinal braking forces. These loads are directed in the positive y- and xdirections, respectively, as shown. The lateral boundary conditions indicated are consistent with the manner in which these lateral loads would be resisted by the structure. Also, the x-directional restraints are defined such that longitudinal braking forces cause compressive stresses in the top chords. Since top chord stresses due to vertical loads are entirely compressive, these boundary conditions represent a conservative assumption.

The other significant assumptions used in formulating Bridge Model 2 are identical to those specified for Model 1 in Section 3.3.8.

3.6 Model Verification

3.6.1 Bridge Models

Verification of finite element results obtained from Bridge Models 1 and 2 has been performed via three independent methods:

(1) Using the SPLT computer program, the finite element meshes have been plotted and carefully checked for proper nodal point locations and member connectivity. (2) A SAP IV verification run was performed for both models. Two 2.75 kip vertical loads were applied at midspan, one at each top chord. (This load is equivalent to a single vehicle tire load of 5.5 kips.) The results were then scrutinized for inconsistencies. Because both the structure and loads are symmetrical about both the longitudinal and transverse centerlines of the bridge, computed deflections and stresses should be symmetrical, as well. Any asymmetry is an indicator of an error in the model. None was found in either of the two models. The deflected shape was also plotted and checked for irregularities.

(3) Two separate manual solutions were performed for the same loading condition. These solutions are presented and compared with the finite element solution in Appendix A of this report. Midspan deflection is the principal basis for comparison, though top and bottom chord stresses are checked as well. The two manual solutions establish upper and lower bounds for the deflections computed in the finite element analysis. In the first solution, the bridge superstructure is idealized as a statically determinate, plane truss. (See Figure A.1.) Midspan deflection is calculated using the method of virtual work. Because the truss has pinned joints, it clearly has less flexural stiffness than the actual bridge. Thus it provides an upper bound for computed midspan deflection. In the lower bound solution, the bridge is modeled as a twodimensional nonprismatic beam, with a cross section consisting of top and bottom chords only. (See Figure A.2.) The solution is based on elementary beam theory. Again the method of virtual work is used to compute midspan deflection. Because elementary beam theory neglects shear distortions and incorporates the assumption that plane sections remain plane, the nonprismatic beam model has more flexural stiffness than the actual bridge. Thus this model provides a lower bound for midspan deflection. A comparison of the results of the two manual solutions and the

verification run is provided in Table A.2. As expected, the computed midspan deflection from the finite element analysis is between the upper and lower bounds; moreover, the computed stresses also agree quite well for all three solutions.

Based on the results of these three verification procedures, the two finite element models of the LV/FB superstructure are judged to be valid.

3.6.2 Membrane Deck Models

Verification of the validity of Membrane Deck Models 1 and 2 has also been performed via three independent methods:

(1) Using the ADINA PLOT post-processing program, the finite element meshes have been plotted and checked for proper nodal point locations and member connectivity.

(2) A verification run was performed for each of the four fiber configurations-MEMBRANES A, B, C, and D. In each run, the center of the membrane deck was loaded with a series of vertical concentrated loads representing a 5.5 kip vehicle tire load. The results were checked for static equilibrium by summing the computed forces in the boundary elements. As expected, the sum of the z-direction (vertical) boundary forces equalled the applied load. In Membrane Deck Model 2, the sum of all x- and ydirection boundary forces equalled zero. The deflected shape of the loaded membrane was plotted with ADINA Plot and checked for inconsistencies.

(3) A manual solution was performed for the same loading condition. This solution is presented in Appendix B, and compared with the results of the finite element solution. Because the actual behavior of the composite membrane deck is quite complex, the manual solution is only a rough approximation. The intent is to

establish upper and lower bounds for the deflections computed in the finite element solution. In the manual solution, the membrane deck is idealized as two bands of unidirectional fibers, one longitudinal and one transverse, as indicated in Figure B.1. The bands intersect at the center of the deck, where the tire load is applied. This arrangement, though crude, is a reasonable approximation of the fiber arrangement in MEMBRANE A. The Rayleigh-Ritz method is used to determine the midspan deflection. Upper and lower bounds are established by varying the width of the transverse band. The results of the manual solution agree reasonably well with those of the finite element analysis of MEMBRANE A.

Based on these verification procedures, the two finite element models of the LV/FB composite membrane deck are judged to be valid.

4.1 Determination of Membrane Section Properties

4.1.1 Analytical Approach

Because the designers of the LV/FB have not yet determined the section properties of the composite membrane deck, those properties must be defined in this study. Specific section properties of interest are the thickness and volume fraction of each unidirectional lamina. In Membrane Deck Model 1, these quantities are represented by the cross sectional areas of the nonlinear truss/cable elements. It is not the intent of this investigation to design the composite membrane deck; nonetheless, it is essential that the selected membrane section properties be realistic values. They must be fully consistent with the configuration of the bridge superstructure and with the strength and stiffness of the composite material. Otherwise, the applicability of all subsequent analyses of the composite membrane deck would be questionable.

Determination of appropriate membrane section properties is accomplished through a preliminary finite element analysis. An iterative process is used. The objective is to define the minimum quantity of Kevlar-49 and E-glass fibers, for which maximum fiber stresses do not exceed the appropriate allowable stresses and for which deflections are not excessive. The procedure is performed as follows:

(1) A set of section properties is assumed, and finite element properties in Membrane Deck Model 1 are defined accordingly. The fiber orientations specified for MEMBRANE D (E-glass fibers oriented at 0° and 90° to the longitudinal axis; Kevlar-49 fibers oriented at $\pm 45°$) are used. The thicknesses and volume fractions of Kevlar-49 and E-glass laminae are assumed to be equal.

(2) The finite element model is loaded with a single critical vehicle tire load, as

specified in the Trilateral Code. This loading is discussed in Section 4.1.2.

(3) The computed maximum deflection is checked. Allowable deflection is governed by the geometry of the LV/FB superstructure. The vertical distance between the top edges of the top chords and the top edge of the uppermost cross member is 4.5 inches. (See Figure 2.) Membrane deflection in excess of 4.5 inches would result in damage to the cross members, which are not designed to carry directly applied vehicle loads. Allowing for initial sag in the membrane and possible overload, a maximum deflection of 3.5 inches is assumed to be acceptable.

(4) The computed maximum fiber stress is checked. The Trilateral Code specifies maximum allowable strains, rather than stresses; however, since the stressstrain relationship of both Kevlar-49 and E-glass is virtually linear from zero to ultimate stress, maximum allowable stresses and strains are proportional. The Trilateral Code defines maximum allowable fiber strain as 50% of the ultimate fiber strain. Thus allowable stresses are 230 ksi for Kevlar-49 and 250 ksi for E-glass.

(5) Based on the computed deflections and fiber stresses, membrane section properties are modified for the next iteration. Cross sectional areas of all nonlinear truss/cable elements are increased or reduced, as required, and the finite element analysis is repeated for the same loading condition. Iterations are performed in this manner, until either the allowable deflection or allowable fiber stresses approach their limiting values.

(6) The quantity of Kevlar-49 and E-glass assumed in the final iteration is translated into appropriate membrane section properties. These are assumed for all subsequent analyses.

4.1.2 Loads

Appendix C of The Trilateral Code specifies critical vehicle loads, axle loads, and tire loads for various NATO Military Load Classes, from MLC 4 to MLC 120. For all analyses involving Membrane Deck Model 1, the critical vehicle tire load for MLC 8 is used. Use of the tire load is appropriate, because these analyses are concerned with local behavior of a portion of the LV/FB's deck. Use of the MLC 8 load is conservative. Though the LV/FB is to be classified as MLC 7, the code does not specify loads for this class.

Figure 33 shows the critical vehicle tire load for MLC 8, as specified in the Trilateral Code. Throughout this report, the contact area between the tire and the deck is referred to as the *footprint*. The code provides only the total load (5500 pounds), the nominal tire width (12.0 inches), and the maximum tire pressure (100 psi). The actual shape and corresponding longitudinal dimension of the footprint must be assumed.

The corresponding finite element representation of the MLC 8 critical vehicle tire load is shown in Figure 34. The nature of the finite element discretization of Membrane Deck Model 1 dictates that the distributed load applied by the tire must be idealized as a series of equivalent concentrated nodal loads. Because the footprint is positioned astride two axes of symmetry, the sum of all concentrated loads is 1375 pounds, one quarter of the 5500 pound load specified for MLC 8. The oval-shaped footprint is simplified as a hexagon. The magnitudes of individual loads are proportioned by computing the reactions of hypothetical simply-supported beams spanning the nodal points in the longitudinal and transverse directions, and loaded with the 100 psi distributed tire load.

Figure 35 shows the ADINA user-defined load function used for the

determination of membrane section properties. Loads are applied in 32 steps, as indicated. The curve is normalized; the maximum ordinate is one. Initial load increments are extremely small, in recognition of the very small out-of-plane stiffness of the undeflected membrane. Subsequent load increments increase dramatically, just as the stiffness of the membrane increases with progressively larger out-of-plane displacements.

4.1.3 Results

The final results of the iterative determination of membrane section properties are summarized in Table 1. These results were achieved in four iterations. Assumed cross sectional areas of nonlinear truss/cable elements, maximum computed deflection, and maximum fiber stresses are provided for the final iteration. Note that maximum deflection, Kevlar-49 fiber stress, and E-glass fiber stress are at or near their allowable values. In fact, the maximum E-glass fiber stress actually exceeds the allowable stress by three percent. This minor overstress is of no concern, because the analysis was performed for the MLC 8 (rather than MLC 7) critical vehicle tire load.

The element cross sectional areas given in Table 1 can be easily converted into equivalent membrane section properties. For example, if the volume fraction is 25%, the equivalent lamina thickness is 0.01 inches, and the total membrane thickness (four laminae) is 0.04 inches. Computed element cross sectional areas also represent a total quantity of Kevlar-49 and E-glass material in the composite membrane deck. This total quantity is held constant in all subsequent analyses of the membrane.

4.1.4 Findings

This simple preliminary analysis is intended only as a precursor to detailed

studies of membrane behavior; nonetheless, it yields a significant finding: Design of the composite membrane deck must simultaneously consider maximum deflection, Kevlar-49 fiber stress, and E-glass fiber stress. Of these three quantities, no single one overwhelmingly controls the design of the membrane, at least in the case of MEMBRANE D.

4.2 Effects of Kevlar-49 and E-Glass Fiber Orientation

4.2.1 Analytical Approach

The following analytical approach is used to determine the effects of fiber orientation on the behavior of the composite membrane deck:

(1) Four separate versions of Membrane Deck Model 1 are prepared. Section properties of the nonlinear truss/cable elements are defined such that the fiber orientations specified for MEMBRANES A, B, C, and D (see Section 2.3.3) are represented. The total amount of Kevlar-49 and E-glass is the same for all four membranes.

(2) Each model is loaded with the MLC 8 critical vehicle tire load, and four separate finite element analyses are performed.

(3) Computed membrane boundary forces (stress resultants in the boundary elements) are used to evaluate and compare the load distribution characteristics of the four membranes. The values of these forces, in kips, are divided by the spacing between elements, in inches, and plotted against the longitudinal positions of the corresponding boundary elements. The plotted curves represent the distributed loads, in kips per inch, applied to the superstructure by the composite membrane deck, in all three global directions.

(4) Computed deflections for all four membranes are plotted and compared.

(5) Computed fiber stresses for all four membranes are represented graphically and compared.

(6) Computed membrane boundary forces for the four membranes are applied as nodal loads to the top chord of Bridge Model 1. One finite element analysis is performed; four load cases are used, one for each set of membrane boundary forces. Note that all four load cases are equivalent to loading the LV/FB with a single axle load at midspan-hardly a realistic loading condition. This analysis is not intended to determine the structural response of the bridge superstructure, but rather to evaluate the *relative* effects of different fiber orientations on the top chords. Thus only the *relative* magnitudes of the computed results are of interest in this phase of research.

(7) To provide a basis for comparison, a second finite element analysis of Bridge Model 1 is performed, this time with two 2.75 kip concentrated loads applied to the top chords at midspan. In this case, the total *vertical* load of 5.5 kips is exactly equal to that of the other four load cases, but there are no loads applied in the other two global directions.

(8) Computed stress resultants in the top chord are plotted against a longitudinal coordinate and compared for all five cases. Maximum normal stresses due to each stress resultant are computed and compared.

(9) Based on a subjective evaluation of (3), (4), (5), and (8), an optimum fiber orientation is selected. This is, of course, not an *absolute* optimum. It is merely the best of four alternatives, selected on the basis of a simplified analytical model. It is left to the designers of the LV/FB to select a membrane configuration which most suitable, in terms of structural requirements, operational requirements, serviceability, and cost. The primary reason for selecting a single fiber orientation in this study is so that subsequent research phases may proceed.

4.2.2 Loads

The magnitude and configuration of loads used in this analysis are as described in Section 4.1.2. The ADINA load function is also identical.

4.2.3 Results

4.2.3.1 Distribution of Applied Load to Top Chord

The composite membrane deck applies a complex distributed load to the top chord of the LV/FB. Use of boundary elements oriented in the global x-, y-, and zdirections in Membrane Deck Model 1 makes it possible to evaluate that distributed load in terms of its three orthogonal components. Those components are defined here as the vertical (z-direction), transverse (y-direction), and longitudinal (x-direction) load distributions.

Figure 36 shows the vertical load distribution for MEMBRANES A, B, C, and D: The longitudinal coordinate represents the location along the edge of Membrane Model 1. A longitudinal coordinate of 75 inches corresponds to midspan of the LV/FB Static equilibrium requires that the area under all four curves be equal. Yet the shapes of the four curves are quite different, indicating very clearly that fiber orientation has a substantial effect on the load distribution characteristics of the composite membrane deck. The vertical load distribution of MEMBRANE A is characterized by its steep slope and large maximum ordinate. The effect on the superstructure is nearly that of a concentrated load applied at midspan. Conversely, the load distribution for MEMBRANE B has the smallest maximum ordinate, located 15 inches away from midspan. The load distribution curves for MEMBRANES C and D lie between these two extremes.

The transverse load distribution for MEMBRANES A, B, C, and D is shown in Figure 37. The shapes of the four plots are very similar to those of the corresponding vertical load distribution curves. However, in each case, the maximum ordinate of the transverse distributed load is over 450% higher. It is reasonable to conclude that, by its very nature, the composite membrane deck applies very substantial lateral loads to the top chords of the LV/FB superstructure. For symmetrical loading conditions, the lateral forces applied to the two chords are always equal and opposite and always directed inward, toward the longitudinal axis of symmetry. Thus the lateral distributed loads are self-equilibrating.

Figure 38 shows the longitudinal load distribution for the four membranes. The relative magnitudes of the four maximum ordinates are exactly opposite those of the vertical and transverse load distributions. MEMBRANE B applies the largest longitudinal loads to the top chord, while MEMBRANE A applies virtually none. Again the load distributions for MEMBRANES C and D lie between the two extremes The direction of the longitudinal loads is always toward the point of application of the tire load; i.e., toward the transverse axis of symmetry. Thus, like the lateral loads, the longitudinal loads are always self equilibrating. They have the net effect of applying a distributed compressive axial load to the top chord.

Comparison of the three sets of load distribution curves leads to the conclusion that there is no obvious "best" fiber configuration. Assuming that "best" is defined as the lowest maximum ordinate on a given load distribution curve, then MEMBRANE. B has the best vertical and transverse load distributions, but the worst longitudinal distribution. MEMBRANE A has the best longitudinal distribution, but the worst distribution in the other two directions. Clearly, improvement in vertical and transverse load distribution is achieved at the expense of increased longitudinal loads. For this reason, it is necessary to evaluate the relative effects of these loads on the top chord of the bridge superstructure. This evaluation is described in Section 4.2.3.4.

4.2.3.2 Deflections

The deflected shape of Membrane Deck Model 1 at the final load step is shown in Figure 39. The undeformed membrane is indicated with dashed lines. This particular mesh plot is for MEMBRANE D, though the general deflected shapes of the other three membranes are not significantly different. For the purpose of comparison, two-dimensional plots of nodal point deflections along the longitudinal and transverse axes of symmetry have been developed as well.

Figures 40 and 41 show the deflection profiles along the longitudinal and transverse axes of symmetry, respectively, for MEMBRANES A, B, C, and D. Maximum deflections range from 3.2 inches for MEMBRANE C to 3.5 inches for MEMBRANE B. In general, the two membranes which have longitudinal, transverse and diagonal fibers (C and D) deflect noticeably less than the other two. This is particularly important, given that deflections are one of the controlling factors in membrane design.

The load-deflection behavior of the composite membrane deck for MLC 8 tire loading is illustrated in Figure 42. The curve is generated from the interim results of an analysis of MEMBRANE D. Each data point represents the maximum deflection at a single ADINA load step. While the plot does not contribute to the selection of an optimum fiber orientation, it does illustrate quite effectively the membrane's nonlinear behavior, as well as its tendency to stiffen as it undergoes out-of-plane displacement.

4.2.3.3 Fiber Stresses

Fiber stresses in MEMBRANES A, B, C, and D are depicted graphically in Figures 43, 44, 45, and 46, respectively. Computed stresses in the nonlinear truss/cable elements in Membrane Deck Model 1 are indicated. A different line weight is used for each order of magnitude of fiber stress. Heavier lines represent higher stresses. Lines are omitted entirely when stresses are less than 0.1 ksi.

These diagrams serve both to complement and to validate the load distribution plots discussed in Section 4.2.3.1. Whereas the load distribution plots show the distribution of loads at the supports of the membrane, the fiber stress diagrams show the paths by which loads are distributed to the supports. In all cases, the load distribution plots and fiber stress diagrams are quite consistent. For example, the orientation of the heavy lines ($\sigma \ge 100$ ksi) in Figure 43 suggests that most of the load applied at the center of MEMBRANE A is transmitted directly to the chords at midspan; the load distributions for MEMBRANE A in Figures 36, 37, and 38 confirm this conclusion.

Computed fiber stresses in the four membranes are summarized in Table 2. Maximum fiber stresses and corresponding percentages of the allowable stress for each fiber type are indicated. In all cases, maximum fiber stresses occur in the immediate vicinity of the applied tire loads. Because the finite element discretization is not configured to provide highly accurate results in this region, these computed stresses should be regarded as only approximate. Nonetheless, they provide considerable information about the relative merits of the four membranes.

MEMBRANE D is the only one of the four which fully utilizes the strengths of both fiber types. MEMBRANES A and C develop substantial overstress in the Kevlar49 fibers, while the E-glass fiber stresses are well below the allowable level. For MEMBRANE B, all fiber stresses are well below the allowable level. However, the lower stresses represent no significant advantage, because the maximum deflection for MEMBRANE B is already at the limiting value of 3.5 inches. There is no potential for improved economy through reduction of fiber content. The full strength of the composite fibers can never be utilized, because the design of MEMBRANE B is controlled by deflection constraints. It is concluded that MEMBRANE D represents the best balance of fiber stresses and maximum deflections. It is well balanced because it permits both fiber types to approach their allowable levels without occurrence of excessive deflections. The configuration of MEMBRANE D is most consistent with the relative advantages of both fiber types; Kevlar-49's high stiffness and E-glass's capacity for elastic elongation are both fully utilized.

4.2.3.4 Stress Resultants and Stresses in Top Chord

Execution of a SAP IV finite element analysis yields six stress results at each end of all beam elements. These stress resultants are given in local coordinates for each element.

Figure 47 shows the orientations of the local coordinate axes and stress resultants for a typical beam element in the center bay portion of the top chord. The full finite element mesh for Bridge Model 1 is included for reference. Local coordinate axes are designated 1, 2, and 3. The stress resultants are axial force, R_1 ; shears, R_2 and R_3 ; torque, M_1 ; and bending moments, M_2 and M_3 . The assumed positive directions are indicated.

For simplicity, only R_1 , M_2 , and M_3 are considered in this particular analysis. These are the stress resultants which contribute to normal stress in the top chord. While significant shear stresses are also developed in the top chord, they are small in comparison with the accompanying normal stresses. R_1 , M_2 , and M_3 provide sufficient basis for comparison of the load distribution characteristics of the four membranes. Detailed treatment of shear stresses is deferred to the analysis of global bridge behavior described in Chapter 5.

Figure 48 shows the longitudinal variation of axial force (R_1) in the top chord of Bridge Model 1, with two 2.75 kip vertical concentrated loads applied at midspan. The longitudinal coordinate is identical to that of the membrane load distribution plots (Figures 36, 37, and 38). This plot represents the axial force in the top chord due solely to the global flexure of the bridge. Because no transverse or longitudinal loads are applied in this case, the curve provides a convenient basis for comparison of the relative effects of the four membranes on the top chord. The steps in the curve occur at the locations of the uprights; at these points, additional axial force is transmitted to the top chord by the diagonal cable braces and uprights. The maximum axial force (19.0 kips compression) is quite substantial. Given that the cross sectional area of the top chord is 1.13 square inches, the normal stress due to axial force alone is 16.8 ksi.

Figures 49, 50, 51, and 52 show the longitudinal variation of R_1 in the top chord of Bridge Model 1, loaded with membrane boundary forces from MEMBRANES A. B. C, and D, respectively. A comparison of these curves with that of Figure 48 clearly illustrates the substantial detrimental effect of the longitudinal loads applied to the superstructure by the membrane. MEMBRANE A, which applies only very small longitudinal loads, produces an R_1 curve very similar to the one produced by loading the bridge with vertical concentrated loads alone. The axial force at midspan is only 9% higher. Conversely, MEMBRANE B, which applies large longitudinal loads to the superstructure, produces a vastly different R_1 distribution. In this case, the maximum
axial force is 40% higher than that of Figure 48. Maximum normal stress due to axial force alone is 23.5 ksi for this case. The R_1 plots for MEMBRANES C and D show the less severe effects of moderate longitudinal loads. Numerical results are summarized in Table 3.

Figure 53 shows the longitudinal variation of bending moment M_3 in the top chord of Bridge Model 1, with two 2.75 kip vertical concentrated loads applied at midspan. Essentially, this plot is the M_3 moment diagram for the top chord, due to the global flexure of the bridge. The maximum bending moment (8.76 kip-inches) occurs at midspan. Given that the sectional modulus of the top chord is 0.779 inch³, the maximum normal stress due to bending alone is 11.2 ksi.

Figures 54, 55, 56, and 57 show the longitudinal variation of M_3 in the top chord of Bridge Model 1 loaded with membrane boundary forces from MEMBRANES A, B, C, and D, respectively. A comparison of these curves with Figure 53 illustrates the membrane's beneficial effect on top chord moments. In all five cases, the total vertical load applied to the bridge is 5.5 kips; yet when that load is applied by the four membranes, top chord moments are reduced by over 20%. This reduction is caused by two factors—(1) the distribution of vertical loads by the membrane and (2) the addition of negative moments due to local bending of the top chord between uprights The differences between the maximum moments for the four membranes are not significant. MEMBRANE D produces the smallest moment (6.27 kip-inches). But the largest moment, produced by MEMBRANE B, occurs 18 inches away from midspan, where top chord axial force is somewhat lower. It is sufficient to conclude that, while all four membranes have a beneficial effect on top chord moments, none is clearly better than the others, in this respect. All results are summarized in Table 3.

Figures 58, 59, 60, and 61 show the longitudinal variation of bending moment

 M_2 in the top chord of Bridge Model 1 loaded with membrane boundary forces from MEMBRANES A, B, C, and D, respectively. No corresponding plot is provided for the case of two 2.75 kip concentrated loads applied at midspan, because $M_2 \approx 0$ for the full length of the top chord in this case. It is reasonable to conclude that M_2 is essentially independent of the global flexure of the bridge due to vertical loads. M_2 is, in fact, local lateral bending due to transverse distributed loads applied by the membrane. This conclusion is consistent with the four M_2 curves. MEMBRANE A, with the largest transverse loads, produces by far the largest M_2 bending moment in the top chord. Similarly, MEMBRANE B, with the smallest transverse loads, produces the smallest maximum M₂. MEMBRANE A's maximum moment of 17.7 kip-inches is particularly significant. Normal stress due to this bending moment alone is 22.7 ksi. When combined with the normal stress due to R_1 , total normal stress is 41.0 ksi. This is nearly equal to the yield stress for Aluminum 7005. Given that the applied vertical load used for this analysis is only a single axle load, MEMBRANE A is clearly an unacceptable alternative. Its inability to adequately distribute transverse loads makes it unsuitable for use as the composite membrane deck of the LV/FB. Maximum M_2 bending moments for MEMBRANES C and D, though larger than for MEMBRANE A, are not so large as to disqualify these fiber configurations. All results are summarized in Table 3.

4.2.3.5 Overstress in Uprights

During a routine check of the Bridge Model 1 finite element results for the analysis described above, unexpectedly high stresses were found to occur in the uprights near midspan. For MEMBRANE B, maximum stress in the midspan upright is 68.5 ksi, which is 50% over yield stress for Aluminum 7005. For MEMBRANES A. C, and D, maximum stresses are even higher. Two factors contribute to this overstress:

(1) The transverse loads applied to the top chord by the membrane cause large bending moments in the uprights where they join the upper cross members.

(2) The oval-shaped cross section of the uprights has a very small flexural moment of inertia with respect to moments in this direction.

Because the analysis was performed for a single MLC 8 critical vehicle tire load (without considering impact effects, dead load, wind load, etc.), occurrences of stresses in excess of yield should certainly not be expected. Thus it is concluded that the configuration of the uprights in the current design does not provide adequate resistance to transverse loads. This is a significant design deficiency. Its discovery caused a temporary halt in the investigation. At this point, any further analysis of the existing LV/FB design would have been of little value, since some form of redesign was clearly required.

In the interest of continuing work on the project, a recommended design change was developed. The change consists of replacing the oval-shaped uprights with 3 inch diameter circular sections, identical to the top and bottom chords. The 3 inch tubes are used for *all* uprights, because the tire load can be applied anywhere along the length of the bridge. This change was incorporated into Bridge Model 1 and the finite element analysis was repeated. Thanks to a substantial increase in flexural moment of inertia, the new computed stress in the midspan upright for the MEMBRANE B load case was 23.2 ksi, which is safely below allowable stress of 33.8 ksi. The recommendation was presented to BRDEC and approved. All subsequent analyses incorporate the revised upright cross section. Implementation of this design change is discussed in more detail in Section 6.3.

4.2.4 Selection of Optimum Fiber Configuration

In selecting an optimum membrane fiber configuration, two of the four alternatives can be eliminated quite easily. MEMBRANE A is disqualified because of its poor transverse load distribution characteristics. Its severe transverse loads cause excessively high local stresses in the top chord. MEMBRANES A and C both have a very poor balance of maximum fiber stresses. When loaded with the MLC 8 critical vehicle tire load, maximum stresses in the Kevlar-49 fibers exceed allowable stress, while maximum stresses in the E-glass fibers are well below the allowable level. For MEMBRANE C this imbalance might be corrected, to some extent, by changing the relative quantities of the two fiber types. Note, however, that the effect of increasing the quantity of Kevlar-49 and decreasing the quantity of E-glass would be to create the same sort of adverse lateral load distribution characteristics exhibited by MEMBRANE A. Clearly MEMBRANES A and C are not acceptable alternatives.

A case might be made for selection of either MEMBRANE B or MEMBRANE D as the best alternative. MEMBRANE B has more favorable vertical and transverse load distribution; MEMBRANE D has better longitudinal load distribution. Analysis of the effects of these loads on stresses in the top chord does little to solve the dilemma. Because of its larger longitudinal loads, top chord normal stresses due to axial load (R_1) are 2.1 ksi higher for MEMBRANE B. Because of its less favorable transverse load distribution, top chord normal stresses due to lateral bending (M_2) are 2.4 ksi higher for MEMBRANE D. The difference is not significant, in comparison with total top chord normal stresses of approximately 30 ksi. MEMBRANE B has lower fiber stresses, but MEMBRANE D has a better balance of fiber stresses and deflections, as is discussed in Section 4.2.3.3. The only aspect of behavior in which one

fiber configuration is clearly superior is the magnitude of maximum deflection. Maximum deflection for MEMBRANE D is 9% lower than for MEMBRANE B.

It is primarily on the basis of maximum deflection, then, that MEMBRANE D is selected as the optimum fiber orientation. This fiber orientation is used for all subsequent analyses.

4.2.5 Findings

Significant findings of this analysis of the effects of fiber orientation are as follows:

(1) Fiber orientation does, in fact, have a substantial impact on the load distribution characteristics of the composite membrane deck. However, no single fiber configuration produces the best load distribution in all three global directions. In general, improvement in vertical and transverse load distribution is achieved at the expense of less favorable longitudinal load distribution.

(2) The transverse loads applied to the top chord by the membrane are roughly proportional to the vertical loads, but approximately 4.5 times as large.

(3) The two membrane types with fibers oriented in all four directions (MEMBRANES C and D) exhibit maximum deflections 5-10% less than the membranes with fibers oriented in only two directions.

(4) MEMBRANE D is selected as the optimum fiber orientation, of the four alternatives considered.

(5) Substantial overstress occurs in the uprights when the bridge is loaded with the MLC 8 critical vehicle tire load. This overstress can be eliminated by changing the uprights from the current configuration to 3 inch diameter tubes.

4.3 Effects of Variation of Tire Load Footprint Configuration

4.3.1 Analytical Approach

The interaction between a vehicle tire and the composite membrane deck is a complex contact stress problem. The discretization of Membrane Deck Model 1 dictates that this interaction must be greatly simplified. The tire load is idealized as a series of concentrated vertical nodal loads, as discussed in Section 4.1.2. To ensure that membrane analyses performed in this manner are valid, it is necessary to consider the impact of this idealization on computed stress resultants and deflections. This is accomplished through a simple parametric study. Four different tire load footprint configurations are defined, and their effects on load distribution, stresses, and deflections are compared.

Figure 62 shows a comparison of the longitudinal deflection profile of the composite membrane deck and the outline of a typical MLC 8 vehicle tire. The deflection profile is taken from the previous membrane analysis. (See Figure 40.) Only the portion of the profile in the immediate vicinity of the tire load is shown. Deflections are normalized, with maximum deflection equal to -1. Note that the tire outline does not appear to be circular, because the horizontal and vertical scales are different. The intent of the figure is to identify the extent to which the computed membrane deflections deviate from the shape of the tire. Clearly the two curves do not coincide, though the discrepancy between them is not large.

In the parametric study, one alternative tire load configuration is defined by forcing the membrane to assume the circular shape of the vehicle tire in the vicinity of the footprint. It is assumed that deformation of the tire is negligible. This assumption is based on the Trilateral Code provision which specifies 100 psi tire pressure. Because the high-pressure tire is nearly rigid and the composite membrane deck has essentially no flexural stiffness, it is expected that the membrane will conform to the tire, not vice versa.

The analytical approach used to define the effects of variation of tire load configuration is as follows:

(1) The tire load configuration defined in Section 4.1.2 is designated FOOTPRINT 1.

(2) The loads defined in Section 4.1.2 are artificially redistributed such that the total vertical load is unchanged, but the computed deflection of the membrane approximately matches the tire outline in the vicinity of the footprint. This is accomplished through a trial-and-error procedure. The final tire load configuration is designated FOOTPRINT 2.

(3) Two other tire load configurations are defined and designated FOOTPRINTS 3 and 4. The principal criterion for these loads is that they be significantly different from FOOTPRINTS 1 and 2.

(4) Finite element analyses are performed for Membrane Deck Model 1, loaded with each of the four footprints.

(5) Load distribution curves and deflection profiles are plotted and compared for all four footprints.

4.3.2 Alternative Tire Load Footprints

FOOTPRINT 1 is shown in Figure 63. It is identical to the tire load configuration defined for investigation of membrane section properties. The assumed footprint shape is hexagonal.

FOOTPRINT 2 is shown in Figure 64. An assumed footprint shape is not

indicated, because these concentrated loads are adjusted from those of FOOTPRINT 1, without regard to tire contact area. This configuration was achieved by trial-and-error in three iterations. Compared with FOOTPRINT 1, the three concentrated loads which are applied along the transverse axis of symmetry are reduced by 15%. The other three concentrated loads are increased accordingly. The net effect is to redistribute load away from the transverse axis of symmetry.

FOOTPRINT 3 is shown in Figure 65. In this configuration, the vertical concentrated loads are exactly equal to those of Footprint 1; however, longitudinal loads are added. This configuration is based on the recognition that tire loads are applied normal to the surface of the deck; thus they are not necessarily vertical. Rather, if the tire does not deform significantly, the tire loads are directed radially outward from the center of the wheel. In FOOTPRINT 3, radially directed concentrated loads are assumed to act as shown in the figure. The angle at which the loads are applied is small (10°), so the vertical components are identical to the vertical concentrated loads.

FOOTPRINT 4 is shown in Figure 66. This configuration is a further simplification of FOOTPRINT 1, achieved by assuming a rectangular footprint, rather than a hexagonal one.

The ADINA user-defined load function used in this study is identical to the one used in the determination of membrane section properties. (See Figure 35.)

4.3.3 Results

Figures 67, 68, and 69 shown the vertical, transverse, and longitudinal load distribution curves, respectively, for Membrane Deck Model 1 loaded with the four

different tire footprints. The differences between the four curves on each plot are so small that individual curves are hardly distinguishable. It is concluded that variations in the configuration of the tire footprint have no substantial effect on distribution of applied load to the top chord.

A comparison of maximum deflections and fiber stresses for the four footprints is provided in Table 4. Again differences between corresponding quantities are insignificant. It is concluded that variations in the configuration of the tire footprint have no substantial effect on maximum deflections or fiber stresses in the composite membrane deck.

The longitudinal deflection profiles for the four footprints are compared to the MLC 8 vehicle tire outline in Figure 70. Note that only the FOOTPRINT 2 deflection curve matches the tire outline reasonably well. Addition of longitudinal loads in FOOTPRINT 3 caused no significant change in deflections. The simplified configuration of FOOTPRINT 4 actually caused further deviation of the deflection profile from the desired shape. A significant conclusion is that *it is not necessary to accurately model the interface between the tire and the composite membrane deck.* Even for substantial changes in the deflected shape of the contact surface, no significant variation occurs in membrane load distribution characteristics or fiber stresses.

4.3.4 Findings

The important finding of this parametric study is that, for a given vehicle tire load, variations in the configuration of the footprint produce no significant variations in the distribution of loads to the top chord, in maximum fiber stresses, or in maximum deflections.

4.4 Effects of Displacement of Top Chords

4.4.1 Analytical Approach

In all analyses of the composite membrane deck described thus far, it is assumed that the membrane's supports—the top chords—remain rigid as loads are applied to the deck. This is, of course, not correct. The top chords undergo substantial displacements under load. They deflect vertically, due to global flexure of the bridge. To a lesser degree, they undergo local vertical deflections between the uprights, due to direct application of vertical loads by the membrane. Similarly, they deflect laterally, due to transverse membrane loads. Twisting of the top chords causes additional lateral displacement of their top edges, where the composite membrane deck is attached. Longitudinal displacement of the top chord also occurs. It is the result of both axial compression due to global flexure and applied longitudinal membrane loads.

Because the behavior of the composite membrane deck is geometrically nonlinear. equilibrium must be established in the displaced position. For this reason, it is expected that top chord displacements will affect the behavior of the membrane under load. The validity of all previously performed membrane analyses is subject to question, until the effects of top chord displacements are determined. This is accomplished through a parametric study.

The analytical approach used to perform this study is as follows:

(1) Top chord displacements are defined. They are the displacements computed for Bridge Model 1, during the analysis of the redesigned uprights, as described in Section 4.2.3.5. Thus these displacements correspond to MLC 8 critical tire loading. This loading condition is used because it produces larger lateral displacements than the critical vehicle load (described in Chapter 6). (2) Membrane Deck Model 1 is modified so that forced boundary displacements can be applied. Very large concentrated loads are applied in the three global directions at each boundary nodal point. The magnitudes of these loads are individually defined, such that the axial deformation of the corresponding boundary elements will exactly equal the prescribed top chord displacements at that nodal point. Because the boundary elements are very stiff, additional boundary displacements due to membrane loads are very small. The ADINA user-defined load function is also modified, so that top chord displacements can be applied in appropriate increments.

(3) The modified Membrane Deck Model 1 is loaded with the MLC 8 critical tire load (FOOTPRINT 1), and the finite element analysis is executed.

(4) Load distribution plots are developed for each incremental application of top chord displacements. Using this technique, the progressive variation of load distribution can be observed.

(5) Membrane deflections for the final load step are plotted.

4.4.2 Application of Top Chord Displacements

Figure 71 shows the vertical nodal point displacements applied to the top chord boundary of Membrane Deck Model 1. Note that these are relative displacements for the center bay only. To reduce the model's susceptibility to instability, rigid body translation of the center bay due to deflections of the ramp bays and end ramp bays is ignored.

Transverse nodal point displacements applied to the top chord boundary of Membrane Deck Model 1 are shown in Figure 72. The effect of local bending of the top chord between the uprights is apparent. Figure 73 shows the longitudinal nodal point displacements applied to the top chord boundary of Membrane Deck Model 1. This plot represents the cumulative effect of axial compression of the top chord. Again, relative displacements for the center bay are used; rigid body translation of the center bay is ignored.

The ADINA user-defined load function used in this parametric study is illustrated in Figure 74. Two separate loading curves are used, one for the vehicle tire load and one for the top chord displacements. The tire load curve is nearly identical to the one used for all previous membrane analyses. To improve the efficiency of computations, it is compressed from 32 to 30 load steps. Top chord displacements are applied in four equal load steps, as indicated by the linear load curve. These displacements are not applied until the tire load is fully applied. This is another attempt to prevent instability in the finite element model. One effect of the top chord displacements is to negate the prestressing of the nonlinear truss/cable elements, resulting in loss of out-of-plane stiffness. By applying the full tire load first, the full out-of-plane stiffness of the membrane model is developed prior to the application of top chord displacements.

Despite all attempts to prevent instability in the finite element model, every execution of the analysis failed in the 33rd or 34th load step. As top chord displacements were applied, local unstable regions developed in the portion of the model farthest removed from the tire load. Typical occurrences of membrane instability is illustrated in Figure 75.

Careful analysis of the results of the failed analyses confirmed the cause of the instability. In the loaded end of the finite element model, substantial out-of-plane stiffness is gained as a result of vertical displacement of the mesh; in the unloaded portion of the membrane, where vertical deflections are negligible, out-of-plane stiffness

is gained primarily from the small prestress applied to the nonlinear truss/cable elements in the formulation of the model. When longitudinal and transverse boundary displacements are applied, the tensile prestress is negated. At any nodal point where all prestress vanishes, instability develops.

Two options were available to solve the problem. The first-and simplest-was to increase the prestress in the nonlinear truss/cable elements until the instability was eliminated. This would facilitate successful execution of the finite element analysis, but would also produce erroneous results. The second option is based on the recognition that occurrence of instability in the finite element model is, in fact, a realistic representation of the behavior of the actual membrane. An unstable nodal point in the model simply represents a local slack region in the composite membrane deck under load. The slack region-a wrinkle or sag-does not participate in the distribution of loads through the membrane. (The situation is analogous to the slack cable in each pair of diagonal cable braces in the bridge superstructure.) The best solution to the instability problem, then, was to simply remove the unstable portions of the finite element model.

Removal of local unstable regions in the finite element model is accomplished quite effectively through the use of ADINA's "Element Birth and Death" option. Using this option, all nonlinear truss/cable elements within an unstable region are simply deleted at the start of the particular load step in which the instability occurs. Several trials are required to identify all unstable regions. Obviously, members must be removed such that the remaining structure is statically stable. As a result, it is possible that more of the membrane may be deleted than is absolutely necessary. This is not a significant concern, because removal of too many elements is conservative, with regard to load distribution characteristics of the membrane.

The removal of unstable regions from Membrane Deck Model 1 is illustrated graphically in Figure 76. All finite elements contained within the shaded portions of the mesh are deleted at Load Steps 33 and 34, as indicated. Using this scheme, the finite element analysis can be fully executed, with no occurrence of instability. The portion of the model which remains at the end of Load Step 34 can then be used to evaluate load distribution and deflection of the membrane.

4.4.3 Results

Figure 77 shows the variation of vertical load distribution as top chord displacements are applied (for Load Steps 30 through 33). For clarity, the final vertical load distribution (Load Step 34) is presented on a separate plot in Figure 78. The curve for Load Step 30 is the load distribution immediately prior to application of top chord displacements. Each successive load step represents an increment of 25% of the total applied displacements. Points of zero distributed load on the curve for Load Steps 33 and 34 correspond to deleted regions of the finite element model. The great similarity of all five curves indicates that vertical load distribution of the composite membrane deck is not significantly affected by top chord displacements.

Figure 79 shows the variation of transverse load distribution as top chord displacements are applied (for Load Steps 30 through 33). The transverse load distribution for Load Step 34 is shown in Figure 80. The curves indicate a gradual decrease in transverse loads as top chord displacements occur. The scalloped shape of the last three curves is caused by local bending of the top chords between the uprights. At midspan, the overall reduction in transverse load is 15%. If the interaction of the membrane and superstructure is fully considered, however, the final reduction will be somewhat less. Reduction in transverse loads will cause a proportional reduction in transverse displacement of the top chord. Reduced displacements will in turn cause a smaller reduction in transverse loads. The exact reduction could be computed quite precisely by performing an iterative series of analyses with Membrane Model 1 and Bridge Model 1. That level of precision is not justified in this study, however. The general trend is quite clear from Figures 79 and 80: top chord displacements cause a 10-15% reduction in transverse load distribution.

Figure 81 shows the variation of longitudinal load distribution as top chord displacements are applied (for Load Steps 30 through 33). Longitudinal load distribution for Load Step 34 is shown in Figure 82. For successive load steps, the peak of the curve tends to shift to the left. The curves for Load Steps 33 and 34 also show the effects of removal of unstable portions of the finite element mesh. Nonetheless, the load distributions at Load Steps 30 and 34 are not substantially different. It is concluded that longitudinal load distribution of the composite membrane deck is not significantly affected by top chord displacements.

Figure 83 shows the deflected shape of Membrane Deck Model 1 at Load Step 34, with top chord displacements applied. The vertical scale is exaggerated. Forced displacement of the boundary is discernable at the lower left.

The longitudinal deflection profiles of the top chord and the membrane centerline at Load Step 34 are shown in Figure 84. Maximum deflection of the membrane with respect to the top chord is 3.93 inches, a 17% increase over the maximum deflection without top chord displacements. As with reduction of transverse load distribution. this value may be reduced somewhat when full interaction of the composite membrane deck and superstructure are taken into account.

4.4.4 Findings

The significant findings of this parametric study are summarized as follows:

(1) The vertical and longitudinal load distributions of the composite membrane deck are not significantly affected by displacements of the top chord.

(2) Displacements of the top chord tend to reduce the transverse load distribution by 10-15%.

(3) Maximum membrane deflection is increased by as much as 17% by displacements of the top chord.

(4) Based on (1) and (2) above, it is concluded that the use of rigid supports in membrane analyses is quite accurate for determination of vertical and longitudinal load distributions and errs on the conservative side for transverse load distributions. The results of previously conducted membrane analyses are judged to be valid, though conservative; subsequent analyses will continue to use the assumption that the top chords do not displace.

5. INVESTIGATION OF BRIDGE BEHAVIOR

5.1 General Analytical Approach

The general analytical approach used in this investigation of global behavior of the LV/FB is as follows:

(1) Design loads are defined in accordance with the provisions of the Trilateral Code. Wherever possible, these specifications are followed exactly. In the instances for which the Trilateral Code does not provide sufficient information, conservative assumptions are made. Definition of design loads includes an analysis of the relative severity of the various live load types.

(2) An analysis is performed to determine the critical vehicle load positions.

(3) Specific finite element load cases are defined.

(4) For each case, appropriate loads are applied to Membrane Deck Model 2 and a finite element analysis is performed. Load distributions and deflections are plotted. It is important to recognize that, because the composite membrane deck behaves nonlinearly, the principal of superposition is not applicable. As a result, the effects of individual design loads cannot be summed algebraically to obtain the effects of combined loads.

(5) A preliminary analysis of Bridge Model 2 is performed to determine which diagonal cable braces are active for each load case.

(6) Slack cable braces are deleted from the model, as required. Membrane boundary forces from (4) are applied to the top chord of Bridge Model 2, and a final finite element analysis is performed for each case.

(7) Pertinent stresses and deflections are computed and plotted.

5.2 Design Loads

5.2.1 Dead Load

The dead load of the LV/FB consists of the combined weights of the superstructure and the composite membrane deck. In Bridge Model 2, superstructure weight is computed automatically by the finite element program. The weight of the composite membrane deck is represented by concentrated loads applied to the top chords. The weights of hinges, latches, turnbuckles, and deck end plates are ignored.

5.2.2 Vehicle Load

The LV/FB is designated as MLC 7; however, the Trilateral Code does not specify design vehicle loads for this load class. Thus it is necessary to modify the loads given for MLC 8.

The design vehicle load for MLC 8, as specified in the Trilateral Code, is shown in Figure 85. The hypothetical vehicle has six equal tire loads, spaced as shown. Each tire load is 3 kips. The design vehicle load is changed to MLC 7 by multiplying all tire loads by $\frac{7}{8}$. Wheel and axle spacing is not changed. There is no provision for this procedure in the code; it is an assumption. It is, however, consistent with the other design vehicle loads specified in the code. The total weight of the MLC 4 design vehicle load is exactly 50% of the total weight of the MLC 8 vehicle. Linear interpolation between these two values is certainly reasonable.

The Trilateral Code also specifies that an impact factor be applied to vehicle loads. The applicable impact factor is 1.15. Thus each tire load for the hypothetical MLC 7 vehicle load is

$$(3 \text{ kips}) \times (\frac{7}{8}) \times (1.15) = 3.01875 \text{ kips}.$$
 (5.1)

Since Bridge Model 2 is a discretization of only one half of the LV/FB, no more than three tire loads are applied to the finite element model in any one load case. The longitudinal position of these loads is defined such that maximum top chord stresses are produced. Laterally, the loads are centered on the longitudinal axis of the deck for all analyses. It is assumed that the large deflections of the loaded membrane cause the tires to center themselves. This is reasonable given that, for a deflection of 3 inches, the slope of the composite membrane deck on either side of the tire is approximately 1:4. The assumption of laterally centered tire loads is also consistent with the geometry of the superstructure and the wheel spacing of the design vehicle. Center-tocenter spacing of the two halves of the LV/FB is 71 inches. (See Figure 1.) Specified minimum lateral spacing of the design vehicle tire loads is 70 inches.

Figure 86 shows the finite element representation of one MLC 7 vehicle tire load used with Membrane Deck Model 2. There are two different configurations, designated Footprint A and Footprint B. Footprint A is used when the tire load is longitudinally centered on a nodal point, and Footprint B is used when the tire load is centered between two nodal points. The magnitudes of the individual concentrated loads are computed in the manner described in Section 4.1.2. The shape of the footprint is assumed to be rectangular and a tire pressure of 100 psi is used.

5.2.3 Mud and Snow Load

The Trilateral Code specifies that mud load shall be taken as $15.65 \text{ pounds/ft}^2$ applied over the entire roadway area. For the LV/FB, the roadway area is the assumed to be the full area of the deck.

Snow load is defined as 7.7 pounds/ ft^2 , but it is only to be used if it has a greater effect than mud load. Such is not the case for the LV/FB, so snow load is

disregarded.

5.2.4 Wind Load

The Trilateral Code defines wind pressure as 5.11 pounds/ft^2 applied to the bridge and crossing vehicle. Because the projected area of the bridge itself is very small and all members are tubular, only the wind effects on the crossing vehicle are considered. The side wind area and center of pressure height for a MLC 10 vehicle are given as 174.5 ft² and 72.0 inches, respectively. These values are used without modification, because no values are given for a load class less than MLC 10. Interpolation is not possible, and extrapolation is potentially unconservative. Given the wind pressure, side wind area, and center of pressure height, wind loads can be translated into appropriate transverse and vertical loads applied to the deck via the vehicle tires.

Figure 87 shows the free body diagram used to compute wind load effects. The forces indicated on the diagram are defined as follows:

W = total design vehicle weight = 15750.0 pounds

 F_w = resultant wind force = (5.11 pounds/ft²)×(174.5 ft²) = 981.7 pounds

- H_d = horizontal reaction at the downwind tire
- $H_u =$ horizontal reaction at the upwind tire
- V_d = vertical reaction at the downwind tire
- $V_u =$ vertical reaction at the upwind tire.

It is clear that V_d is somewhat larger than V_u , and thus the downwind side represents the critical case. Using elementary statics, V_d and H_d are computed. The horizontal reactions are assumed to be proportional to their respective vertical reactions. (This assumption is slightly more conservative than the assumption that the horizontal reactions are equal.) The downwind vertical reaction due to wind, $(V_d)_w$, is the computed, using

$$\left(\mathbf{V}_{\mathbf{d}}\right)_{\mathbf{w}} = \mathbf{V}_{\mathbf{d}} - \frac{\mathbf{W}}{2}.$$
 (5.2)

 $(V_d)_w$ and H_d are the total vertical and horizontal wind-induced forces applied to the deck by the downwind vehicle tires. Assuming that these loads are distributed equally to all three downwind tires, wind loads applied at each tire footprint are obtained by dividing both $(V_d)_w$ and H_d by 3. The results are

$$\frac{(V_d)_w}{3} = 261.0$$
 pounds, and $\frac{H_d}{3} = 163.4$ pounds

5.2.5 Braking Force

The Trilateral Code defines longitudinal braking force as the vehicle load times a braking factor. It is applied at the deck surface. The impact factor is not included. The braking factor is given as 0.5. Thus for a each vehicle tire, the longitudinal braking force for MLC 7 is

$$(3.0 \text{ kips}) \times (\frac{7}{8}) \times (0.5) = 1.313 \text{ kips}.$$
 (5.3)

5.2.6 Total Design Load

The total design load, P, is defined in the Trilateral Code as

$$\mathbf{P} = \mathbf{D} + \mathbf{A}_1 + \mathbf{0.8A}_2 + \mathbf{0.6A}_3 + \mathbf{0.4A}_4 , \qquad (54)$$

where D is the dead load, and A_1 , A_2 , A_3 , A_4 are live loads, arranged in order of decreasing severity. Applicable live loads are vehicle load, mud load, wind load, and braking load, as defined in Sections 5.2.2 through 5.2.5.

In order to fully define P, it is necessary to evaluate the relative severity of the four live load types. In this investigation, severity of loads is evaluated in terms of the behavior of the top chords, because these members have been identified as critical. (See

Section 2.4.) The most severe load type is defined as the one which causes the largest stresses in the top chords.

By inspection, it is clear that vehicle load is the most severe. Thus A_1 is defined as vehicle load in Equation (5.4). The relative severity of the other three live loads, however, is by no means obvious. Not only are the three load types very different in configuration and direction, but wind load and braking load can be applied anywhere along the length of the bridge. A rational analysis is required to determine A_2 , A_3 , and A_4 .

The relative severity of mud load, wind load, and braking load is evaluated via a simple manual analysis. The task could have been accomplished with a much higher degree of precision by perfoming a series of finite element analyses, using Membrane Deck Model 2 and Bridge Model 2. However, the expense of such a procedure would not be justified, given the relatively low level of precision required for determination of load severity.

Figure 88 shows the simple analytical model used for evaluation of the relative severity of loads. The LV/FB superstructure is idealized as a simply supported beam. The cross section of the beam consists of only the top and bottom chords, as shown in Section A-A. Cross sectional area and flexural moments of inertia in both directions are indicated. Using these section properties and elementary beam theory, approximate stresses in the top chords can be calculated for each load type. (This same procedure was used for manual verification of Bridge Models 1 and 2, and produced reasonably accurate results.)

The analysis of severity of loads is presented in detail in Appendix C. The results are quite conclusive. Of the three live load types under consideration, mud load causes the largest top chord stresses and thus is most severe. Wind load is ranked next

in severity, and braking load is last. Therefore, the total design load, P, for the LV/FB is defined as

$$P = D + V + 0.8M + 0.6W + 0.4B, \qquad (5.5)$$

where

D = dead load V = vehicle load M = mud load W = wind load (on crossing vehicle) B = longitudinal braking load.

This ranking of loads is also consistent with the likelihood that the LV/FB will actually experience the full specified design loads during normal use. Because of the substantial deflection of the composite membrane deck under load, it is expected that a large quantity of mud will be retained on the deck. The specified mud load is therefore realistic. Conversely, it is unlikely that the full specified wind load will be experienced. The actual vehicle for which the LV/FB is intended, the HMMWV, has a substantially smaller side wind area and a lower center of pressure than the Trilateral Code specifies. Likewise, it is unlikely that the full specified braking load will be experienced. The braking factor provided in the code is based on a crossing speed of 15 miles per hour. Because of the flexibility of the LV/FB-the deck, in particular-it is expected that vehicles will actually cross at a slower speed.

5.3 Critical Vehicle Load Positions

5.3.1 Analytical Approach

Before the design load response of the LV/FB can be evaluated, it is necessary to identify the position or positions of the MLC 7 vehicle load which cause the largest stresses in the top chord. This is accomplished via a finite element analysis of Bridge Model 1. Bridge Model 1 is used, rather than Bridge Model 2, because it has a finer top chord discretization in the center bay, where maximum stresses are expected to occur.

The analytical approach used in determining critical live load positions is as follows:

(1) Twenty representative load positions are defined at regular intervals along the length of the bridge.

(2) Each load position is formulated as a separate finite element load case. For simplicity, only vertical loads are applied to the top chords of Bridge Model 1. No attempt is made to represent the vertical, transverse, and longitudinal distribution of loads by the composite membrane deck. Consideration of membrane load distribution would require a separate nonlinear finite element analysis for each live load position. The complexity and expense of such an analysis is not justified here; the simpler procedure is sufficient to establish the *relative* effects of vehicle load position on top chord stresses.

(3) One finite element analysis is performed. The analysis has 20 load cases.

(4) Results of the analysis are formulated into plots which depict top chord normal stress as a function of vehicle load position, for individual segments of the top chord. These plots are used to identify the critical load positions.

Figure 89 shows the twenty representative vehicle load positions used to identify critical load positions. For each load position, three arrows are used to indicate the positions of the MLC 7 vehicle tire loads. Longitudinal sections are shown below for reference. Vehicle Load Positions 3 through 9 are spaced at 6 inch intervals. (It was expected that the critical load position would occur in this region. This expectation

turned out to be only partially correct.) Most of the remaining load positions are spaced at 15 inch intervals. There is some variation, due to the irregular spacing of nodal points in the ramp bays.

5.3.2 Results

Figure 90 and 91 show plots of maximum top chord normal stress as a function of vehicle load position for the center bay. For reference, the center bay is divided into ten segments. They are identified in terms of the longitudinal sections defined in Figure 1. For example, Segment M-N is the 15 inch length of the top chord which extends from Section M to Section N. There is one curve for each segment. For a given curve, each data point represents the maximum normal stress which occurs within that segment for a particular load position. These curves are similar in concept to influence lines, except that the full MLC 7 vehicle load, rather than a unit load, is applied. Comparison of all ten curves yields the conclusion that maximum normal stresses are generated in the center bay portion of the top chord when the vehicle load is at Position 8. Maximum stresses occur in Segment Q-R.

Figure 92 and 93 show maximum top chord normal stress as a function of vehicle load position for a ramp bay. Again the bay is divided into segments, identified in terms of the longitudinal sections indicated in Figure 1. Comparison of the nine curves yields the conclusion that maximum normal stresses are generated in the ramp bay portion of the top chord when the vehicle load is at Position 11. Maximum stresses occur in Segment DD-EE.

Figure 94 shows maximum top chord normal stress as a function of vehicle load position for Segments K-L-M and W-X-Y. These segments represent the center bay/ramp bay interface. Because of the unique geometry of the top chord in these segments, they are given special treatment. Recall that the continuity of the top chord is broken at Sections L and X, where the latches are located. As a result of this lack of continuity, normal stresses in Segment K-L-M are the highest in the entire bridge. This portion of the LV/FB is identified as a potential design deficiency and is given special attention in all subsequent analyses. The curve for Segment K-L-M yields the conclusion that maximum normal stresses are generated at the center bay/ramp bay interface when the vehicle load is at Position 5.

In general, then, this analysis has determined that there are three critical vehicle load positions. They are Positions 5, 8, and 11. None of these can be safely discounted. Absolute maximum stresses occur at the center bay/ramp bay interface for Position 5; however this is a local condition, which can be improved somewhat via a minor design change. The maximum stresses due to loading at Positions 8 and 11 are nearly equal. Clearly the design of the LV/FB is well balanced; as a result, the maximum top chord normal stress occurs in both the center and ramp bays. A detailed investigation of global bridge behavior requires that the MLC 7 vehicle load br applied at all three critical positions.

5.4 Finite Element Load Cases

The finite element load cases used to investigate global behavior of the LV/FB are as follows:

LOAD CASE I: DEAD LOAD LOAD CASE II: VEHICLE LOAD (Position 5) LOAD CASE III: VEHICLE LOAD (Position 8) LOAD CASE IV: VEHICLE LOAD (Position 11) LOAD CASE V: TOTAL DESIGN LOAD [P=D+V(Position 5)+0.8M+0.6W+0.4B]

LOAD CASE VI: TOTAL DESIGN LOAD [P=D+V(Position 8)+0.8M+0.6W+0.4B]LOAD CASE VII: TOTAL DESIGN LOAD[P=D+V(Position 11)+0.8M+0.6W+0.4B]

5.5 Effects of Design Loads on Composite Membrane Deck

5.5.1 Load Case I

For the membrane section properties established in Section 4.1, the equivalent distributed load due to membrane weight is less than .01 pounds/inch². Because this load is so small in comparison with the total weight of the structure, a dead load analysis of the composite membrane deck is not performed. Membrane weight is considered in the final Load Case I analysis, but only by applying equivalent vertical loads to the top chord nodal points of Bridge Model 2.

5.5.2 Load Case II

The vertical load distribution curve for Load Case II is shown in Figure 95. The longitudinal coordinate is the location along the longitudinal edge of Membrane Deck Model 2. Midspan is at a longitudinal coordinate of 75 inches. The ordinates of the curve are equal to the computed stress resultants in the vertical boundary elements. divided by the distance between elements. Because Load Case II loads are symmetrical with respect to the longitudinal centerline of the deck, the distribution of loads to both chords is equal. The single curve in Figure 95 describes the vertical load distribution for both chords. The two large peaks in the curve occur because two tires of the MLC 7 vehicle are located very close to the deck end plates. The result is a very abrupt distribution of vertical loads to the top chord. Note also that the vertical load distribution is actually positive (directed upward) in portions of the ramp bay. This is due to the ramp's slope, which is accurately represented in Membrane Deck Model 2. In the ramp bay, the inclined membrane exerts a slight upward pull on the portion of the top chord farthest from the point of application of the tire load.

Transverse and longitudinal load distribution curves for Load Case II are shown in Figures 96 and 97, respectively. The transverse load distribution is dominated by the effect of the center tire of the MLC 7 vehicle. An interesting feature of the longitudinal load distribution curve is its frequent reversals of direction. In general, the longitudinal loads always reverse direction at the point of application of each tire load and again somewhere between each pair of tire loads.

Figure 98 shows the deflected shape of Membrane Deck Model 2 for Load Case II. The vertical scale is exaggerated. The effect of the three tire loads is clearly visible.

The longitudinal deflection profile of the deck centerline for Load Case II is shown in Figure 99. As expected, the maximum deflection of 2.45 inches is significantly smaller than the deflections computed for the MLC 8 critical tire load in Section 4.2.3.2.

5.5.3 Load Case III

The vertical, transverse, and longitudinal load distribution curves for Load Case III are shown in Figure 100, 101, and 102, respectively. As in Load Case II, the presence of the deck end plates causes local peaks in the vertical load distribution curve. In Load Case III, however, the peaks are substantially lower, because the MLC 7 vehicle tires are located farther from the end plates. As a result, a larger proportion of the vertical loads are distributed directly to the top chords. Positive vertical load distribution still occurs at the extreme end of the ramp bay. The magnitude of the transverse load distribution is significantly higher than in Load Case II. Figures 103 and 104 show the deflected shape and longitudinal deflection profile, respectively, of Membrane Deck Model 2 for Load Case III. Note that the shape of the deflection profile is *peaked* at the front tire, but *abruptly truncated* at the rear tires. The difference occurs because the front tire load is centered on a nodal point, while each of the rear tire loads is centered between two nodal points. Two different footprint configurations are used, as discussed in Section 5.2.2. The apparent discrepancy is of no concern. The analysis described in Section 4.3 indicates that such variations in footprint configuration have no significant effect on computed load distributions.

5.5.4 Load Case IV

The vertical, transverse, and longitudinal load distribution curves for Load Case IV are shown in Figure 105, 106, and 107, respectively. Figures 108 and 109 show the corresponding deflected shape and longitudinal deflection profile, respectively.

5.5.5 Load Case V

The vertical, transverse, and longitudinal load distribution curves for Load Case V are shown in Figure 110, 111, and 112, respectively. Load Case V loads include wind load, which is not symmetrical with respect to the longitudinal centerline of the deck. As a result, the load distributions are different on the upwind and downwind sides. In all three figures, the two load distribution curves are plotted on a single set of axes. Upwind side and downwind side are indicated, though in two of three cases the ordinates of the curve are so close that the two curves appear as one. A comparison of these load distribution curves with the Load Case II curves (Figures 95, 96, and 97) provides a good indication of the combined contribution of mud, wind, and braking

loads to the total design load.

Figures 113 and 114 show the deflected shape and longitudinal deflection profile, respectively, of Membrane Deck Model 2 for Load Case V. While the maximum deflection is only marginally larger than for Load Case II, the shape of the deflected membrane is substantially different. The fuller deflection profile is caused by the application of mud load to the entire deck.

5.5.6 Load Case VI

The vertical, transverse, and longitudinal load distribution curves for Load Case VI are shown in Figure 115, 116, and 117, respectively. Figures 118 and 119 show the corresponding deflected shape and longitudinal deflection profile, respectively. Again the effects of mud load are quite apparent.

5.5.7 Load Case VII

The vertical, transverse, and longitudinal load distribution curves for Load Case VII are shown in Figure 120, 121, and 122, respectively. Figures 123 and 124 show the corresponding deflected shape and longitudinal deflection profile, respectively.

5.6 Effects of Design Loads on Bridge Superstructure

5.6.1 Preliminary Analysis of Diagonal Cable Braces

A preliminary analysis is required to determine which of the diagonal cable braces are in tension for the various loading conditions. This is accomplished via a single finite element analysis of Bridge Model 2 with six load cases. These are Load Cases II through VII, as defined in Section 5.4. (For Load Case I, the diagonal cable braces in tension can be identified by inspection.) For each load case, computed membrane boundary forces from the corresponding analysis of Membrane Deck Model 2 are applied to the top chord. The results of the analysis are used only to identify which cables are in tension. Computed stress resultants and deflections are not valid.

The diagonal cable braces which are in tension for Load Cases I through VII are shown in Figure 125. The applicable vehicle load positions are shown for reference. Based on these results, four different versions of Bridge Model 2 are prepared. All cable braces not shown in Figure 125 are "deleted" by assigning the appropriate truss elements a very small modulus of elasticity. (Cross sectional area is not reduced, so that dead loads are not affected.)

5.6.2 Final Analyses

The final finite element analyses are executed for Load Cases I through VII, using the modified versions of Bridge Model 2. In these analyses, the following loads are used, as required:

- (1) Membrane boundary forces computed for Load Cases II through VII
- (2) Automatically computed dead loads
- (3) Concentrated loads representing the weights of the composite membrane deck and deck end plates.
- (4) Concentrated loads representing the mud load which is applied to the solid deck on the two end ramp bays, and to the single composite membrane deck segment on which no tire loads are applied.

Computed stress resultants are used to calculate normal and shear stresses in the top chords, bottom chords, uprights, and cross members. Because of the complex. three-dimensional behavior of the LV/FB, there are many locations at which maximum stresses might occur in each of these components. In this investigation, all potential

locations of maximum stresses are checked for the top chords; the most likely locations of maximum stresses are checked for the bottom chords, uprights, and cross members.

Figure 126 shows the eight specific points at which stresses are calculated for each load case. The following terms are used in the figure and throughout the remainder of this report to identify these particular locations of calculated stresses:

- (1) Top of the Top Chord
- (2) Bottom of the Top Chord
- (3) Outside of the Top Chord
- (4) Inside of the Top Chord
- (5) Bottom of the Bottom Chord
- (6) Inside of the Upright
- (7) Top of the Top Cross Member
- (8) Side of the Top Cross Member

While it may not be readily apparent, maximum stresses could possibly occur at any of these points. This is particularly true for the top chord, which is susceptible to the combined effects of vertical global bending of the bridge, transverse (wind-induced) global bending of the bridge, longitudinal loads, and both local bending and local twisting due to directly applied membrane loads. For Load Cases V through VII, stresses at these eight locations are different on the upwind and downwind sides of the bridge. In all cases, there is significant longitudinal variation of these stresses as well. In most instances, significant normal and shear stresses occur simultaneously; thus the effects of combined stresses must be considered.

5.6.3 Results

The results of this series of finite element analyses are organized by load case and presented as a series of standardized graphs. These are contained in Figures 127 through 190. These graphs depict longitudinal variation of stresses and representative deflection profiles. For each load case (except Case I), a standard "package" of ten figures is presented, as follows:

- (1) Longitudinal variation of normal and shear stress at the top of the top chord.
- (2) Longitudinal variation of normal and shear stress at the bottom of the top chord.
- (3) Longitudinal variation of normal and shear stress at the outside of the top chord.
- (4) Longitudinal variation of normal and shear stress at the inside of the top chord.
- (5) Longitudinal variation of normal and shear stress at the bottom of the bottom chord.
- (6) Normal stress and shear stress at inside of the uprights.
- (7) Normal stress at the top of the top cross members.
- (8) Normal stress at the side of the top cross members.
- (9) Vertical deflection of the top chord.
- (10)Transverse deflection of the top chord.

The sequence and format of these graphs is the same for Load Cases II through VII. The results of Load Case I are adequately described by (1), (5), (6), and (9) above.

In the succeeding sections of this report, general trends and key points are highlighted for each load case. No attempt is made to describe individual graphs. Maximum normal and shear stresses are summarized in Table 4.

5.6.3.1 Load Case I

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Results for Load Case I are presented in Figures 127 through 130. These figures depict longitudinal variation of significant stresses and vertical deflection of the top chord. Stresses in the top and bottom chords are plotted with respect to a longitudinal coordinate axis, which represents the total length of the bridge. Midspan is at 220 inches. Stresses in the uprights are presented on a bar graph, because these are discrete values rather than continuously varying quantities.

The maximum normal stresses for Load Case I are 1.2 ksi (tension) at the bottom of the bottom chord and 1.1 ksi (compression) at the top of the top chord. Shear stress at these locations is negligible. Normal and shear stresses in the uprights are also very small. Quite clearly, dead load has very little influence on the behavior of the LV/FB.

5.6.3.2 Load Case II

Results for Load Case II are presented in Figures 131 through 140. These figures depict the longitudinal variation of stresses and representative deflection profiles.

From Figures 131 through 134, maximum normal stress in the top chord is determined to be 34.1 ksi (compression). It occurs at the top of the member, in the region where the center bay and ramp bay are connected. Shear stress at this location is less than 0.1 ksi. This result is consistent with the selection of critical vehicle load positions (Section 5.3). Load Position 5 was specifically selected because it caused maximum normal stresses at the center bay/ramp bay interface. The next largest normal stress in the top chord is 31.2 ksi, a reduction of 9% from the absolute maximum. This observation supports the conclusion that high stresses in the top chord at the center bay/ramp bay interface are caused by a local design deficiency. They are not necessarily indicative of the global behavior of the LV/FB.

Figures 133 and 134 clearly show the effects of local transverse bending of the top chord in the vicinity of the vehicle tire loads. Very high local normal stresses occur

as a result. Stresses at the bottom of the bottom chord are consistently lower than the corresponding values at the top of the top chord, as is shown in Figure 135. This can be attributed primarily to the absence of longitudinal and transverse membrane loads in the bottom chords. Note that, unlike the top chords, the center bay/ramp bay interface has the effect of reducing stresses.

As indicated in Figure 136, normal stresses in the uprights also show the effect of transverse bending in the vicinity of the vehicle tire loads. The maximum normal stress (22.6 ksi) occurs in the upright at Section P. This value is reasonably low, thus confirming the adequacy of the design change recommended in Section 4.2.3.5. Note the strong correlation between stresses in the uprights and stresses in the top cross members (Figures 137 and 138). Maximum normal stress in the cross members also occurs at Section P, though in this case it is caused by the combined effects of transverse bending and substantial axial compression.

Maximum vertical deflection is quite large-nearly 8 inches-as shown if Figure 139. The transverse deflection profile (Figure 140) shows the significant inward displacement of the top chord due to transverse membrane loads. Irregularities near the two maxima on the curve are the effects of local bending between the uprights.

5.6.3.3 Load Case III

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Results for Load Case III are presented in Figures 141 through 150. These figures depict the longitudinal variation of stresses and representative deflection profiles.

From Figures 141 through 144, maximum normal stress in the top chord is determined to be 32.3 ksi (compression). It occurs at the top of the member, at a longitudinal coordinate of 175 inches. Because this value is larger than the next-tohighest top chord stress in Load Case II, it can be regarded as the maximum live load normal stress in the center bay. Shear stress at this location is 3.2 ksi.

In general, maximum stresses in the bottom chord, uprights, and cross members are slightly higher, by approximately 1 ksi, than the corresponding maximum stresses for Load Case II. Maximum vertical deflection is virtually unchanged.

The most significant finding in the results of Load Case III is the observation of substantial bending of the top chord in the outer portion of the loaded ramp bay. This is clearly visible in the transverse deflection profile (Figure 150) and in the cross member stresses (Figures 147 and 148). The problem is caused by the reduction in the number of cross members per upright from two to one at Section CC, and from one to none at Section FF. (See Figure 4.) A section with two cross members is particularly effective in resisting transverse membrane loads, because the compressive force in the top cross member and the tensile force in the bottom cross member effectively apply large resisting couples to the two uprights. When a section has only one cross member. this is not possible, and resistance to transverse bending is substantially decreased. Note the abrupt drop in cross member stresses at Sections CC, DD, and EE (Figures 147 and 148). While this problem is first observed in the results of Load Case III, it gets significantly worse in Load Case IV, where the front tire of the MLC 7 vehicle is placed directly over Section EE.

5.6.3.4 Load Case IV

Results for Load Case IV are presented in Figures 151 through 160. These figures depict the longitudinal variation of stresses and representative deflection profiles.

From Figures 151 through 154, maximum normal stress in the top chord is
determined to be 36.8 ksi (compression). It occurs at the outside of the member, near the outer end of the loaded ramp bay. This is quite significant, for two reasons. First, it is the absolute largest normal stress occurring in Load Cases II, III, and IV, the three vehicle load cases. Second, because it occurs on the side of the member rather than the top, it is clearly the result of excessive transverse bending of the top chord. This second reason confirms the conclusion suggested by the results of Load Case III: reduction of the number of cross members at the outer sections of the ramp bays constitutes a significant design deficiency. As a result of decreased resistance to transverse membrane loads, excessively large stresses occur in the top chords in these regions.

Larger normal stresses also occur in the bottom chords, as indicated in Figure 155. The maximum normal stress is 33.1 ksi, the highest bottom chord stress for Cases II, III, and IV. Equally significant is the occurrence of bottom chord shear stresses twice as large as in previous load cases.

The transverse deflection profile (Figure 160) clearly illustrates the excessive transverse bending of the top chord in the outer end of the ramp bay. In this region, the maximum deflection is 85% larger than the maximum deflection in the center bay, where transverse loads due to *two* vehicle tires are significantly higher.

5.6.3.5 Load Case V

Results for Load Case V are presented in Figures 161 through 170. These figures depict the longitudinal variation of stresses and representative deflection profiles. All graphs in this section are for the *upwind side*, unless otherwise indicated. Because wind loads are present in this load case, stresses are different in the upwind and downwind sides of the bridge. Computed results indicate, however, that the

differences are not significant (for this load case or for Load Cases VI and VII). Generally, corresponding stresses on both sides of the superstructure vary by less than 1%. Also, stresses are not consistently higher or lower for one particular side. Thus the stresses on either side can be regarded as representative.

From Figures 161 through 164, maximum normal stress in the top chord is determined to be 39.8 ksi (compression). It occurs at the top of the member, at the center bay/ramp bay interface. This location is consistent with the location of maximum stress in Load Case II, though the magnitude of the maximum normal stress is 17% higher for Case V. There is, in fact, a strong similarity between the shapes of the corresponding curves for the two load cases. A comparison of the of these curves yields the conclusion that longitudinal variation of normal stress in the top and bottom chords is nearly identical for Load Cases II and V, except that Case V stresses are uniformly 4-6 ksi larger. This increment in stresses quantitatively represents the combined effect of dead, mud, wind, and braking loads.

Stresses in the uprights and cross members increase slightly as a result of combined loads. For the uprights, the increase is no more than 2 ksi. This is virtually no change in the normal stress at the *tops* of the top cross members; at the sides of these members, however, stresses increase by approximately 2 ksi. This behavior is attributed to the effects of longitudinal braking loads and wind loads.

In Figures 169 and 170, vertical and transverse deflection profiles are shown for both the upwind and downwind sides. The noticeable "kinks" in all four curves occur at the four latches, where the continuity of the top chord is broken. This is another example of the manner in which the global behavior of the LV/FB is affected by the connections between modules. The small difference between the vertical deflection curves suggests that global twisting of the bridge due to wind load is small. The

transverse deflection curves indicate that global transverse bending of the bridge due to wind load is considerably larger than local transverse bending of the of the chords due to membrane loads. Note also the stiffening effect of the end ramp bays. Transverse deflection of these modules is very small. This effect is attributed primarily to the solid deck in these bays, though the lateral boundary conditions defined for Bridge Model 2 also contribute, to some degree. (See Figure 32.)

5.6.3.6 Load Case VI

Results for Load Case VI are presented in Figures 171 through 180. These figures depict the longitudinal variation of stresses and representative deflection profiles. All graphs in this section are for the *upwind side*, unless otherwise indicated.

From Figures 171 through 174, maximum normal stress in the top chord is determined to be 37.8 ksi (compression). It occurs at the top of the member, at a longitudinal coordinate of 175 inches. Thus it is the maximum normal stress in the center bay due to the total design load. Shear stress at this location is 3.4 ksi. The longitudinal coordinate is consistent with the location of maximum stress in Load Case III, though the magnitude of the maximum normal stress is 17% higher for Case V1. The 17% variation is exactly the same as the variation between Load Cases II and V. A similar general conclusion can be drawn, as well: longitudinal variation of normal stress in the top and bottom chords is nearly identical for Load Cases III and V1, except that Case VI stresses are uniformly 4-6 ksi larger.

For Load Case VI, the normal stress at the top of cross member BB (25.2 ksi) is the absolute largest cross member stress for any load case.

5.6.3.7 Load Case VII

Results for Load Case VII are presented in Figures 181 through 190. These figures depict the longitudinal variation of stresses and representative deflection profiles. All graphs in this section are for the upwind side, unless otherwise indicated.

From Figures 181 through 184, maximum normal stress in the top chord is determined to be 42.4 ksi (compression). It occurs at the outside of the member, near the outer end of the loaded ramp bay. This is the absolute largest normal stress which occurs in the LV/FB for any loading condition. Its principal cause is excessive transverse bending, as discussed in Section 5.6.3.4. It is noteworthy, however, that maximum normal stress in the top of the top chord in the end ramp bay is only slightly less (41.8 ksi). Thus a design change which improves the top chord's ability to resist transverse loads will not necessarily produce a substantial improvement.

The magnitude of the maximum normal stress for Case VII is 15% higher than for Case IV. In general, the differences in computed stresses between the vehicle load cases (II, II, and IV) and the corresponding total design load cases (V, VI, and VII) are very nearly equal. It is concluded that the incremental effect of dead, mud, wind, and braking loads is largely independent of live load position. While this conclusion may appear to be a statement of the obvious, it must be remembered that the principal of superposition does not apply to the nonlinear behavior of the composite membrane deck.

For Load Case VII, the normal stress computed for the upright located at Section Q (25.8 ksi) is the absolute largest stress in an upright for any load case.

5.6.4 Combined Stresses and Allowable Stress

The Trilateral Code defines the maximum stress, fy, as

$$f_{v} = \sqrt{f_{x}^{2} - f_{x}f_{y} + f_{y}^{2} + 3f_{s}^{2}} , \qquad (5.6)$$

where

 $f_{\mathbf{X}} = \text{normal stress in the x-direction}$

 $f_v = normal stress in the y-direction$

 $f_s = shear stress.$

As applied to this investigation, Equation (5.6) reduces to

$$f_{v} = \sqrt{\sigma^2 + 3\tau^2} \quad , \tag{5.7}$$

where

 $\sigma = \text{normal stress (longitudinal)}$

 $\tau = \text{shear stress.}$

For all points in the LV/FB at which normal and shear stresses occur simultaneously, it is necessary to compute the maximum stress. Computed values are included in Table 4.

The Trilateral Code also specifies that

$$f_v \le f_{allowable} = \frac{Yield Stress}{1.33}.$$
 (5.8)

Thus for Aluminum 7005

$$f_{allowable} = \frac{45.0 \text{ ksi}}{1.33} = 33.8 \text{ ksi}.$$
 (5.9)

Based on the computed maximum stresses summarized in Table 4, the following conclusions are made:

(1) Maximum stresses in the top chords exceed the allowable stress for Load Cases II, IV, V, VI, and VII. (2) Maximum stresses in the bottom chords exceed the allowable stress for Load Cases IV, V, VI, and VII.

(3) In no case do maximum stresses in the uprights and top cross members exceed the allowable stress.

(4) In no case do maximum stresses in the bridge superstructure exceed yield stress.

5.6.5 Findings

Four major findings of this investigation of the LV/FB comprise an evaluation of the overall capacity of the structure. They are as follows:

The current LV/FB design does not meet the requirements for Military
Load Class 7, as defined in the Trilateral Code.

(2) When the bridge is loaded with the MLC 7 design load, as defined in the Trilateral Code, maximum stresses in the top and bottom chords exceed the allowable stress for Aluminum 7005.

(3) The cross members and redesigned (3 inch diameter tube) uprights have adequate capacity for MLC 7 design load.

(4) When the LV/FB is loaded with the MLC 7 design load, yield stress (0.2% strain) does not occur in any member.

The remaining findings are supplemental in nature. They contributed to the determination of the major findings above and, in two cases, define the specific requirements for recommended design changes. These findings are as follows:

(1) The relative severity of MLC 7 design live loads for the LV/FB is (in order of decreasing severity) vehicle load, mud load, wind load, and longitudinal braking load.

(2) There are three critical positions for the MLC 7 vehicle load. One, designated as Load Position 5, causes maximum stresses in the top chords at the center bay/ramp bay interface. One, designated as Load Position 8, causes maximum stresses in the top chords in the center bay. One, designated as Load Position 11, causes maximum stresses in the top chords in the ramp bays.

(3) The contribution of dead load to maximum stresses in the LV/FB is less than 3%.

(4) The contribution of live loads other than vehicle load to maximum stresses in the LV/FB is approximately 12%.

(5) There is a design deficiency in the configuration of the top chord at the center bay/ramp bay interface which causes locally high stresses in that area. A recommended design change is presented in Section 6.3.

(6) There is a design deficiency in the outer ends of the ramp bays. It is caused by the reduction in the number of cross members at this location. As a result, the top chords have greatly reduced resistance to transverse loads in this region. It is recognized that the configuration of cross members in the current design is dictated by the clearance requirement for vertical deflection of the composite membrane deck. This constraint is taken into account in a recommended design change, presented in Section 6.3.

6. SUMMARY AND CONCLUSIONS

6.1 Summary

The Light Vehicle/Foot Bridge (LV/FB) is a unique, innovative tactical bridging system currently being developed at the U.S. Army Belvoir Research, Development, and Engineering Center at Fort Belvoir, Virginia. Its superstructure is a modular space frame constructed of lightweight aluminum alloy tubing. The LV/FB's removable deck is a flexible composite membrane, composed of Kevlar-49 and E-glass fibers embedded in a neoprene matrix. The intended load capacity of the structure is Military Load Class 7 (MLC 7). Because the system is still under development, certain key aspects of its behavior are still not well understood.

The research reported herein is an investigation of the behavior of the LV/FB under design loading conditions. The basis for the analysis is the <u>Trilateral Design</u> and <u>Test Code for Military Bridging and Gap-Crossing Equipment</u>.

The LV/FB is described in detail in Chapter 2 of this report. Emphasis is placed on unusual aspects of the structure which must be accounted for in developing analytical models. The following characteristics are particularly important:

(1) Nearly every aspect of the LV/FB design is dictated by the operational requirements for light weight, simplicity, and portability.

(2) Because the bridge must be portable, its ten modules are interconnected with a system of hinges and latches which permit the entire structure to be folded and carried on a small trailer. These connections break the continuity of the top and bottom chords in regions of high stress.

(3) To provide adequate clearance for deflections of the composite membrane

deck, few cross members are provided in the outer ends of the ramp bays. As a result, the top chords in these regions are less capable of resisting transverse loads.

(4) The composite membrane deck must carry large vertical loads, despite the fact that is has virtually no flexural or compressive stiffness. The result is substantial geometric and material nonlinearity.

This analysis of the LV/FB is characterized by *separate* consideration of the composite membrane deck and the bridge superstructure. The general analytical procedure consists of three steps. First the behavior of the loaded membrane is investigated, using nonlinear finite element analysis; then the membrane boundary forces (reactions at the edges of the membrane) are determined; finally, these forces are applied to a linear finite element model of the bridge superstructure. This general procedure is used in each of the two major phases of this research.

The first phase is a detailed investigation of the behavior of the composite membrane deck. Membrane section properties are defined, through an iterative series of nonlinear finite element analyses. The same nonlinear finite element model is then used in conjunction with a linear model of the entire bridge to evaluate the effects of the orientations of the composite fibers. An optimum fiber orientation is selected. Finally, two key assumptions which were used in these analyses are validated via simple parametric studies.

The second phase of this research is an investigation of the global behavior of the entire structure, subjected to MLC 7 design loads. It is not an *independent* investigation, as the membrane section properties and optimum fiber orientation defined in the first phase are used. Both linear and nonlinear finite element analyses are performed. The results are organized into a series of standardized graphs, which depict the longitudinal variation of normal and shear stresses in key structural

components, as well as representative deflection profiles. Emphasis is placed on the behavior of the top chords, whose performance largely controls the design of the bridge. Based on these data, the load capacity of the LV/FB is evaluated.

6.2 Conclusions

Based on these interrelated investigations of the behavior of the composite membrane deck and the global behavior of the LV/FB, the following significant conclusions are made:

(1) The current LV/FB design does not meet the requirements for MLC 7, as defined in the Trilateral Code. When the bridge is loaded with MLC 7 design loads, maximum stresses in the top and bottom chords exceed the allowable stress for Aluminum 7005 by a substantial margin, but do not exceed yield stress.

(2) For the uprights specified in the original design, stresses exceed yield stress by a substantial margin; however, with a minor design change, stresses are reduced to well below the allowable level. This design change has been approved by BRDEC and was incorporated into the final investigation of the LV/FB. It consists of replacing the original uprights with the same 3 inch diameter tubes used for the top and bottom chords.

(3) Maximum stresses in the top chords occur at three different locations — in the center bay near midspan, at the outer ends of the ramp bays, and at the center bay/ramp bay interface. Only the first of these is truly indicative of the global behavior of the bridge; the other two are local conditions caused by design deficiencies at those locations.

(4) The behavior of the LV/FB is dominated by the influence of the MLC 7

vehicle load. The influence of dead load is quite small in comparison. The relative contribution of vehicle load to the maximum stress is 86.8%; the contribution of dead load is 2.5%; the contribution of all other live loads (mud load, wind load, and braking load, with appropriate load factors applied) is 10.7%.

(5) The orientation of Kevlar-49 and E-glass fibers in the composite membrane deck has a substantial impact on load distribution characteristics, fiber stresses, and maximum deflections of the membrane. However, none of the four fiber orientations considered in this investigation ranks as the best in all categories.

(6) Of the four alternative fiber configurations considered, the one designated as MEMBRANE D is selected as the optimum. This configuration has equal amounts of Kevlar-49 fibers oriented at $\pm 45^{\circ}$ to the longitudinal axis and equal amounts of E-glass fibers oriented at 0° and 90° to the longitudinal axis. The selection is based on consideration of load distribution characteristics, fiber stresses, and maximum deflections. Two of the four alternatives are easily eliminated; however the final selection is based on a subjective weighing of relative advantages and disadvantages of the two remaining alternatives.

(7) For the fiber configuration designated as MEMBRANE D, a very efficient set of membrane section properties can be defined. It is possible to establish the *membrane thickness* and *volume fraction* such that allowable stress in the Kevlar-49 fibers, allowable stress in the E-glass fibers, and maximum allowable deflection are all achieved for approximately the same applied load.

(8) In performing nonlinear finite element analysis of the composite membrane deck, the configuration of the vehicle tire "footprint" does not have a significant effect on computed fiber stresses or membrane load distribution characteristics.

(9) In performing nonlinear finite element analysis of the composite membrane deck, the assumption that the top chords of the bridge do not displace is conservative, with respect to load distribution characteristics.

6.3 Recommended Design Changes

The results of this investigation indicate that the LV/FB does not meet the requirements for MLC 7, its intended load capacity; however, this conclusion certainly does not imply that the design concept is faulty or even that current design is not viable. In the current design, the operational requirements of light weight, simplicity, and portability are satisfied in an imaginative and highly satisfactory manner. All indications are that, with a few minor design changes, the load capacity of the LV/FB can be brought up to the intended level. It is assumed that the most desirable design changes are ones which cause the least modification to the current structural system. Based on this assumption, specific recommendations for design changes are as follows:

(1) Replace the oval-shaped uprights with 3 inch diameter tubes. This change, discussed in Section 4.2.3.5, is required because the weak-axis moment of inertia of the oval-shaped tubes is too small to resist the large lateral loads applied to the top chords. The 3 inch diameter tubes have been shown to be adequate. Connection of the redesigned uprights to the chords is a potential problem, however, because the members are all the same size. A proposed solution is presented in Figure 191. The mechanical rigidity of the current connection design, as shown in (a), can only be achieved if the ends of the 3 inch diameter uprights are flattened to an oval cross section in the immediate vicinity of the connection. The flattened ends can be passed through holes in the chords and welded, as is indicated in (b). Because the maximum moments occur, not at the chords, but at the cross member connections, local

reduction of the flexural moment of inertia at the ends of the uprights does not affect the adequacy of these members. (Based on consultation with BRDEC, this configuration has been determined to be feasible.)

(2) Lower the required load capacity to MLC 5. This is, of course, the simplest solution to the problem of insufficient capacity, because it involves no design changes other than (1) above. It is a viable solution, because the actual vehicle for which the LV/FB is designed, the HMMWV, is rated as MLC 4. A simple linear interpolation of the results of this investigation suggests that the LV/FB could be rated at MLC 5 with no further modifications. (This conclusion must be verified by a separate MLC 5 analysis.) The obvious disadvantage of this solution is that the bridge cannot be used for vehicles larger than MLC 5. Light Infantry Divisions do, in fact, have such vehicles in limited numbers.

(3) Modify the configuration of the top chords at the center bay/ramp bay interface. The recommended modification is presented in Figure 192. The figure shows, from top to bottom, (a) the current configuration, (b) a simplified analytical model of the current configuration, (c) the free body diagram of the analytical model, and (d) the proposed design change. In (a), the points where high stresses occur are indicated. These locally high stresses are primarily the result of bending moment induced by the change in the orientation of the top chord. This is illustrated by the analytical model and free body diagram in (b) and (c), respectively. In the analytical model, the two members are oriented at the same angles as the two sections of the top chord in (a). For simplicity, the ends are assumed to be restrained from rotation. Even though the only applied load is an axial force, P, substantial moments are generated in the two chord segments, as shown in (c). These moments are somewhat larger than those that would occur in the actual bridge, where some rotation of the members can occur. However, the actual magnitude of these moments is not important; the intent of the analytical model is simply to demonstrate that the geometric arrangement of the center bay/ramp bay interface is such that the axial force in the top chords due to global bending of the bridge generates substantial secondary bending moments. Based on this conclusion, the recommended design change is presented in (d). By simply relocating the break in the continuity of the chord and adding a diagonal cable brace as shown, it is expected that secondary bending moments will be substantially reduced. Minor redesign of the latch mechanism and deck end plates (not shown) will be required, as well.

(4) Enhance the lateral stiffness of the top chords at the outer ends of the ramp bays. The recommended modification is presented in Figure 193. The cross sections shown are typical sections with only one cross member (Sections E, F, G, CC, DD, and EE). The current design is shown in (a). The proposed change, shown in (b), consists of the addition of a transverse steel cable, attached to the uprights where they join the bottom chord. The effect is essentially the same as that of two tubular cross members. It is achieved with minimal added weight, without piercing the bottom chord, and without violating vertical clearance requirements for the composite membrane deck. The cable can be post-tensioned for added effectiveness, as required. Note that the redesigned uprights are included in (b).

(5) Increase the wall thickness of the top and bottom chords. In order to achieve a load capacity of MLC 7, it is necessary to substantially reduce the level of stress in both the top and bottom chords. This can be accomplished with the least amount of change to the current design by increasing the wall thickness of the top and bottom chords. The results of this investigation suggest that a wall thickness of $\frac{3}{16}$ inch will be adequate for both the top and bottom

chords. This wall thickness equates to a 41% increase in flexural moment of inertia and a 47% increase in cross sectional area of the chords. The corresponding increase in total weight is less than 100 pounds for the entire bridge. The adequacy of this design change must be verified, however.

(6) Add an auxiliary cable reinforcing system for loads larger than MLC 5. This is an alternative to (5) above. Given that most crossing vehicles are likely to be MLC 5 or less, it would be possible to use the current LV/FB design for normal mission requirements, but to add a temporary reinforcing kit for larger loads. A suggested auxiliary cable reinforcing system is shown in Figure 194. Removable struts (most likely made of aluminum tubing) are used in conjunction with high-strength steel cables to increase the flexural capacity of the structural system. Manual posttensioning of these cables might be considered. Further analysis is required to determine whether or not such a system is viable.

6.4 <u>Recommendations for Future Research</u>

Much research must yet be performed before the behavior of the LV/FB is fully understood. To a large degree, the nature of future research will be determined by the extent to which the existing configuration is modified in the development of a final design. Specific recommendations for future research are as follows:

(1) Verify the effectiveness and viability of the design changes recommended in Section 6.3. Verification can be performed through a series of finite element analyses The methodology and finite element models described in this report are suitable for these analyses, though minor modifications are required to incorporate the specific design changes.

(2) Validate the nonlinear finite element analyses of the composite membrane

deck through experimental load tests on actual membrane material samples. The correlation between analytical and experimental results will determine the extent to which nonlinear finite element analysis can be reliably used in future membrane studies.

(3) Investigate the behavior of the LV/FB under unusual loading conditions. The most important of these are support settlement (applied in conjunction with design loads), vehicle loads which are off-center in the transverse direction, and overload. Finite element analysis is suitable for this investigation.

(4) Investigate the behavior of the LV/FB in a damaged condition. Pertinent types of damage include fractured tubular frame members, broken welds, fractured hinges, and broken diagonal cable braces. The effects of tearing of the composite membrane deck and separation of its Velcro connection to the top chord might also be studied. Finite element analysis is suitable for this investigation.

(5) Investigate in detail the capacity of the welded connections, hinges, and latches. In particular, the effects of loss of section, stress concentrations, and residual stresses at the connections of tubular frame members should be evaluated. This investigation might be performed via highly detailed finite element analyses, though physical testing of actual components would produce more reliable results.

(6) Investigate the fatigue performance of the structure. Particular attention should be given to welded details and to the composite membrane deck. This investigation is best accomplished by physical testing.

These recommended investigations are, for the most part, logical extensions of the research presented in this report. If performed in conjunction with physical testing of a prototype of the bridge, they will result in a full understanding of the behavior of the LV/FB.



Table 1. Results of Iterative Determination of Membrane Section Properties

······	KEVLAR-49	E-GLASS
Cross Sectional Area (Truss/Cable Elements)	0.005304 in ²	0.007500 in^2
Max Fiber Stress	216.0 ksi	257.5 ksi
% of Allowable Stress	93.9%	103.0%

Maximum Deflection = 3.36 inches

Table 2. Maximum Fiber Stresses in MEMBRANES A, B, C, and D for MLC 8 Critical Vehicle Tire Load

	KEVL.	AR-49	E-GLASS		
MEMBRANE	Max Fiber Stress (ksi)	% of Allowable Stress	Max Fiber Stress (ksi)	% of Allowable Stress	
A	342.2	148.8	217.8	87.1	
В	183.5	79.8	116.8	46.7	
С	376.0	163.5	140.5	5 6.2	
D	216.0	93.9	257.5	103.0	

MEMBRANE	R ₁ (kips)	σ (ksi)	M ₂ (k-in)	σ (ksi)	M 3 (k-in)	σ (ksi)
*None	-19.03	-16.86	0.0	0.0	8.757	11.24
A	-20.69	-18.33	-17.68	-22.69	6.677	8.570
В	-26.64	-23.60	-6.882	-8.832	6.687	8.583
С	-22.99	-20.36	-11.70	-15.02	6.429	8.251
D	-24.29	-21.51	-8.749	-11.23	6.271	8.049
					<u> </u>	

MAXIMUM STRESS RESULTANTS AND STRESSES

Table 3. Maximum Stress Resultants and Stresses in Top Chord for MLC 8 Critical Vehicle Tire Load

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*Two 2.75 kip vertical concentrated loads applied to the top chords at midspan

Table 4. Maximum Deflections and Fiber Stresses in the Composite MembraneDeck Loaded With FOOTPRINTS 1, 2, 3, and 4

FOOTPRINT	Maximum Deflection	Maximum Fiber Stress (Kevlar-49)	Maximum Fiber Stress (E-Glass)		
1	3.36 in	216.0 ksi	257.5 ksi		
2	3.32 in	209.6 ksi	244.1 ksi		
3	3.36 in	218.0 ksi	255.6 ksi		
4	3.32 in	205.8 ksi	258.6 ksi		

Table 5. Maximum Stresses in Bridge Superstructure for Load Cases II-VII

			LOAD CASE					
MEMBER	Location *	Stress **	11	III	IV	v	VII	VIII
TOP	Тор	σ	-34.06	-32.32	-35.62	-39.78	-37.76	-41.78
CHORD		au	0.08994	3.197	2.442	0.2065	3.361	1.546
		f_v	34.06	32.79	35.87	39.78	38.21	41.87
	Bottom	σ	-21.62	-24.24	-24.62	-25.42	-28.12	-29.47
	{	T	0.3388	1.125	2.065	0.3279	1.273	2.210
		f_v	21.63	24.32	24.88	25.43	28.21	29.72
	Outside	σ	-31.03	-30.88	-36.81	-36.79	-36.86	-42.43
		τ	0.2851	0.5650	0.9288	0.3463	0.6206	1.012
		$f_{\mathbf{v}}$	31.03	30.90	36.85	36.79	36.88	42.47
	Inside	σ	-29.14	-30.19	-30.59	-33.06	-34.20	-35.17
	1	7	2.165	2.199	6.264	2.324	2.446	6.770
		f _v	29.38	30.43	32.46	33.30	34.46	37.07
DOTTON	Detter	_	00.00	20.70	22.06	24 61	06 76	20.60
CHORD	Bottom	σ	20.02	30.19	33.00	34.01	30.70	39.02
CHURD		T S	0.0214	0.9082	3.001	0.0148	0.9204	3.420
		I v	20.84			34.03	30.19	40.00
UPRIGHT	Inside	σ	-22.60	-23.63	-24.01	-24.50	-25.37	-25 83
	140140	τ -	0.6352	0 9777	1 000	0 9011	1 431	1 077
		fv	22.63	23.69	24.08	24.55	25.49	25.90
		······						<u> </u>
TOP	Тор	σ	-22.50	-23.44	-21.37	-22.63	-25.20	-23.18
MEMBER	Side	σ	-17.83	-19.12	-8.44	-19.8	-24.3	-22.7

*Locations are as defined in Figure 126.

** $f_v = \sqrt{\sigma^2 + 3\tau^2}$, as defined in the Trilateral Code, and thus is always positive.

8. FIGURES



Figure 1. General Configuration and Overall Dimensions of the Light Vehicle/Foot Bridge

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Figure 2. Typical Cross Section of the Center Bay

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• = CROSS- MEMBER LOCATION







Figure 4. LV/FB in the Travel Mode



Figure 5. Unfolding of the LV/FB



Figure 6. LV/FB Launching Sequence



Figure 7. Configuration of the Welded Connections



Figure 8. Arrangement of a Typical Pair of Diagonal Cable Braces

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Figure 10. Cutaway View of a Typical Latch





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-1.01-

DETAIL A



Figure 12. Stress-Strain Relationship for a Typical Aluminum Alloy



Figure 13. Fiber Configuration for MEMBRANE A



Figure 14. Fiber Configuration for MEMBRANE B



Figure 15. Fiber Configuration for MEMBRANE C



Figure 16. Fiber Configuration for MEMBRANE D



Figure 17. Stress-Strain Relationship for Rubber



Figure 18. Idealized Unidirectional Lamina



Figure 19. Unidirectional Lamina Subjected to In-Plane Shear Loading



DEFLECTED POSITION





Figure 21. Geometrically Nonlinear Behavior Exhibited by the Composite Membrane Deck



Figure 22. Portion of the Composite Membrane Deck Represented by Membrane Deck Model 1



Figure 23. Isometric View of the ADINA Finite Element Discretization of Membrane Deck Model 1





= TRIBUTARY AREA



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Figure 25. Isometric View of the SAPIV Finite Element Discretization of Bridge Model 1






Figure 27. Node Numbering Scheme Used in Bridge Model 1



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Figure 29. Portion of the Composite Membrane Deck Represented by Membrane Deck Model 2



Figure 30. Isometric View of the ADINA Finite Element Discretization of Membrane Deck Model 2



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Figure 32. Structural Boundary Conditions for Bridge Model 2



MAXIMUM TIRE PRESSURE = 100 PSI

Figure 33. Critical Vehicle Tire Load for Military Load Class 8







Figure 35. ADINA User-Defined Load Function Used for Determination of Membrane Section Properties



Figure 36. Vertical Load Distribution for MEMBRANES A, B, C, and D



Figure 37. Transverse Load Distribution for MEMBRANES A, B, C, and D



Figure 38. Longitudinal Load Distribution for MEMBRANES A, B, C, and D



Figure 39. Deflected Shape of Membrane Deck Model 1 at the Final Load Step



Figure 40. Deflection Profile Along the Longitudinal Axis of Symmetry for MEMBRANES A, B, C, and D



Figure 41. Deflection Profile Along the Transverse Axis of Symmetry for MEMBRANES A, B, C, and D



Figure 42. Load-Deflection Behavior of the Composite Membrane Deck for MLC 8 Tire Loading







Figure 44. Fiber Stresses in MEMBRANE B







Figure 46. Fiber Stresses in MEMBRANE D



Figure 47. Orientations of the Local Coordinate Axes and Stress Resultants for a Typical Beam Element in the Center Bay Portion of the Top Chord



Figure 48. Longitudinal Variation of R₁ in the Top Chord of Bridge Model 1, with Two 2.75 Kip Loads Applied at Midspan



Figure 49. Longitudinal Variation of R₁ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE A



Figure 50. Longitudinal Variation of R₁ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE B



Figure 51. Longitudinal Variation of R₁ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE C



Figure 52. Longitudinal Variation of R₁ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE D



Figure 53. Longitudinal Variation of M₃ in the Top Chord of Bridge Model 1, with Two 2.75 Kip Loads Applied at Midspan



Figure 54. Longitudinal Variation of M₃ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE A



Figure 55. Longitudinal Variation of M₃ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE B



Figure 56. Longitudinal Variation of M₃ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE C



Figure 57. Longitudinal Variation of M₃ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE D



Figure 58. Longitudinal Variation of M₂ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE A



Figure 59. Longitudinal Variation of M₂ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE B



Figure 60. Longitudinal Variation of M₂ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE C



Figure 61. Longitudinal Variation of M₂ in the Top Chord of Bridge Model 1, Loaded with Membrane Boundary Forces from MEMBRANE D



Figure 62. Comparison of the Longitudinal Deflection Profile of the Composite Membrane Deck and the Outline of a Typical MLC 8 Vehicle Tire



Figure 63. Tire Load FOOTPRINT 1



Figure 64. Tire Load FOOTPRINT 2









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Figure 67. Vertical Load Distribution for Membrane Deck Model 1, Loaded with Tire Load FOOTPRINTS 1, 2, 3, and 4



Figure 68. Transverse Load Distribution for Membrane Deck Model 1, Loaded with Tire Load FOOTPRINTS 1, 2, 3, and 4



Figure 69. Longitudinal Load Distribution for Membrane Deck Model 1, Loaded with Tire Load FOOTPRINTS 1, 2, 3, and 4





Figure 71. Vertical Nodal Point Displacements Applied to the Top Chord Boundary of Membrane Deck Model 1



Figure 72. Transverse Nodal Point Displacements Applied to the Top Chord Boundary of Membrane Deck Model 1



Figure 73. Longitudinal Nodal Point Displacements Applied to the Top Chord Boundary of Membrane Deck Model 1



Figure 74. ADINA User-Defined Load Function Used for the Parametric Study of Top Chord Displacements



Figure 75. Typical Occurrences of Membrane Instability During Application of Top Chord Displacements



Figure 76. Removal of Unstable Regions from Membrane Deck Model 1



Figure 77. Variation of Vertical Load Distribution as Top Chord Displacements are Applied (Load Steps 30-33)



Figure 78. Variation of Vertical Load Distribution as Top Chord Displacements are Applied (Load Step 34)



Figure 79. Variation of Transverse Load Distribution as Top Chord Displacements are Applied (Load Steps 30-33)



Figure 80. Variation of Transverse Load Distribution as Top Chord Displacements are Applied (Load Step 34)



Figure 81. Variation of Longitudinal Load Distribution as Top Chord Displacements are Applied (Load Steps 30-33)



Figure 82. Variation of Longitudinal Load Distribution as Top Chord Displacements are Applied (Load Step 34)



Figure 83. Deflected Shape of Membrane Deck Model 1 at Load Step 34 with Top Chord Displacements Applied



Figure 84. Longitudinal Displacement Profiles of the Top Chord and Membrane Longitudinal Axis of Symmetry at Load Step 34



Figure 85. Design Vehicle Load for MLC 8








Figure 87. Free Body Diagram Used for Computation of Wind Load Effects



Figure 88. Simple Analytical Model Used for Evaluation of Relative Severity of Loads



Figure 89. Representative Vehicle Load Positions Used to Identify Critical Load Positions

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Figure 90. Maximum Top Chord Normal Stress as a Function of Vehicle Load Position (Segments M-N, N-O, O-P, P-Q, and Q-R)



Figure 91. Maximum Top Chord Normal Stress as a Function of Vehicle Load Position (Segments R-S, S-T, T-U, U-V, and V-W)



Figure 92. Maximum Top Chord Normal Stress as a Function of Vehicle Load Position (Segments Y-Z, Z-AA, AA-BB, BB-CC, and CC-DD)



Figure 93. Maximum Top Chord Normal Stress as a Function of Vehicle Load Position (Segments DD-EE, EE-FF, FF-GG, and GG-HH)

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Figure 94. Maximum Top Chord Normal Stress as a Function of Vehicle Load Position (Segments K-L-M and W-X-Y)



Figure 95. Vertical Load Distribution for Load Case II



Figure 96. Transverse Load Distribution for Load Case II



Figure 97. Longitudinal Load Distribution for Load Case II



Figure 98. Deflected Shape of Membrane Deck Model 2 for Load Case II



Figure 99. Longitudinal Deflection Profile of the Composite Membrane Deck Centerline for Load Case II



Figure 100. Vertical Load Distribution for Load Case III



Figure 101. Transverse Load Distribution for Load Case III



Figure 102. Longitudinal Load Distribution for Load Case III



Figure 103. Deflected Shape of Membrane Deck Model 2 for Load Case III



Figure 104. Longitudinal Deflection Profile of the Composite Membrane Deck Centerline for Load Case III



Figure 105. Vertical Load Distribution for Load Case IV



Figure 106. Transverse Load Distribution for Load Case IV



Figure 107. Longitudinal Load Distribution for Load Case IV



Figure 108. Deflected Shape of Membrane Deck Model 2 for Load Case IV



Figure 109. Longitudinal Deflection Profile of the Composite Membrane Deck Centerline for Load Case IV



Figure 110. Vertical Load Distribution for Load Case V



Figure 111. Transverse Load Distribution for Load Case V



Figure 112. Longitudinal Load Distribution for Load Case V



Figure 113. Deflected Shape of Membrane Deck Model 2 for Load Case V



Figure 114. Longitudinal Deflection Profile of the Composite Membrane Deck Centerline for Load Case V



Figure 115. Vertical Load Distribution for Load Case VI



Figure 116. Transverse Load Distribution for Load Case VI



Figure 117. Longitudinal Load Distribution for Load Case VI



Figure 118. Deflected Shape of Membrane Deck Model 2 for Load Case VI



Figure 119. Longitudinal Deflection Profile of the Composite Membrane Deck Centerline for Load Case VI



Figure 120. Vertical Load Distribution for Load Case VII



Figure 121. Transverse Load Distribution for Load Case VII



Figure 122. Longitudinal Load Distribution for Load Case VII



Figure 123. Deflected Shape of Membrane Deck Model 2 for Load Case VII



Figure 124. Longitudinal Deflection Profile of the Composite Membrane Deck Centerline for Load Case VII



Figure 125 Diagonal Cable Braces which are in Tension for Load Cases I VII



Figure 126. Points at which Stresses are Calculated for Each Load Case



Figure 127. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case I)



Figure 128. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case I)

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Figure 129. Normal Stress and Shear Stress at the Inside of the Uprights (Load Case I)



Figure 130. Vertical Deflection of the Top Chord (Load Case I)



Figure 131. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case II)



Figure 132. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Top Chord (Load Case II)



Figure 133. Longitudinal Variation of Normal and Shear Stress at the Outside of the Top Chord (Load Case II)



Figure 134. Longitudinal Variation of Normal and Shear Stress at the Inside of the Top Chord (Load Case II)



Figure 135. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case II)



Figure 136. Normal Stress and Shear Stress at the Inside of the Uprights (Load Case II)



Figure 137. Normal Stress at the Top of the Top Cross Members (Load Case II)



Figure 138. Normal Stress at the Side of the Top Cross Members (Load Case II)



Figure 139. Vertical Deflection of the Top Chord (Load Case II)



Figure 140. Transverse Deflection of the Top Chord (Load Case II)



Figure 141. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case III)



Figure 142. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Top Chord (Load Case III)



Figure 143. Longitudinal Variation of Normal and Shear Stress at the Outside of the Top Chord (Load Case III)



Figure 144. Longitudinal Variation of Normal and Shear Stress at the Inside of the Top Chord (Load Case III)



Figure 145. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case III)



Figure 146. Normal Stress and Shear Stress at the Inside of the Uprights (Load Case III)



Figure 147. Normal Stress at the Top of the Top Cross Members (Load Case III)



Figure 148. Normal Stress at the Side of the Top Cross Members (Load Case III)

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Figure 149. Vertical Deflection of the Top Chord (Load Case III)



Figure 150. Transverse Deflection of the Top Chord (Load Case III)



Figure 151. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case IV)



Figure 152. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Top Chord (Load Case IV)



Figure 153. Longitudinal Variation of Normal and Shear Stress at the Outside of the Top Chord (Load Case IV)



Figure 154. Longitudinal Variation of Normal and Shear Stress at the Inside of the Top Chord (Load Case IV)



Figure 155. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case IV)



Figure 156. Normal Stress and Shear Stress at the Inside of the Uprights (Load Case IV)



Figure 157. Normal Stress at the Top of the Top Cross Members (Load Case IV)



Figure 158. Normal Stress at the Side of the Top Cross Members (Load Case IV)



Figure 159. Vertical Deflection of the Top Chord (Load Case IV)



Figure 160. Transverse Deflection of the Top Chord (Load Case IV)

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Figure 161. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case V)



Figure 162. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Top Chord (Load Case V)



Figure 163. Longitudinal Variation of Normal and Shear Stress at the Outside of the Top Chord (Load Case V)



Figure 164. Longitudinal Variation of Normal and Shear Stress at the Inside of the Top Chord (Load Case V)



Figure 165. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case V)



Figure 166. Normal Stress and Shear Stress at the Inside of the Uprights (Load Case V)



Figure 167. Normal Stress at the Top of the Top Cross Members (Load Case V)



Figure 168. Normal Stress at the Side of the Top Cross Members (Load Case V)



Figure 169. Vertical Deflection of the Top Chord (Load Case V)



Figure 170. Transverse Deflection of the Top Chord (Load Case V)



Figure 171. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case VI)







Figure 173. Longitudinal Variation of Normal and Shear Stress at the Outside of the Top Chord (Load Case VI)



Figure 174. Longitudinal Variation of Normal and Shear Stress at the Inside of the Top Chord (Load Case VI)



Figure 175. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case VI)







Figure 177. Normal Stress at the Top of the Top Cross Members (Load Case VI)



Figure 178. Normal Stress at the Side of the Top Cross Members (Load Case VI)



Figure 179. Vertical Deflection of the Top Chord (Load Case VI)



Figure 180. Transverse Deflection of the Top Chord (Load Case VI)



Figure 181. Longitudinal Variation of Normal and Shear Stress at the Top of the Top Chord (Load Case VII)



Figure 182. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Top Chord (Load Case VII)

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Figure 183. Longitudinal Variation of Normal and Shear Stress at the Outside of the Top Chord (Load Case VII)



Figure 184. Longitudinal Variation of Normal and Shear Stress at the Inside of the Top Chord (Load Case VII)



Figure 185. Longitudinal Variation of Normal and Shear Stress at the Bottom of the Bottom Chord (Load Case VII)



Figure 186. Normal Stress and Shear Stress at the Inside of the Uprights (Load Case VII)



Figure 187. Normal Stress at the Top of the Top Cross Members (Load Case VII)



Figure 188. Normal Stress at the Side of the Top Cross Members (Load Case VII)

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Figure 189. Vertical Deflection of the Top Chord (Load Case VII)



Figure 190. Transverse Deflection of the Top Chord (Load Case VII)

(a) CURRENT DESIGN



(b) PROPOSED DESIGN CHANGE



Figure 191. Recommended Modification of Uprights



Figure 192. Recommended Modification of Top Chords at the Center Bay/Ramp Bay Interface

(a) CURRENT DESIGN



(b) PROPOSED DESIGN CHANGE



Figure 193. Recommended Modification of Outer Ends of Ramp Bay





9. <u>REFERENCES</u>

1. ADINA Engineering

ADINA USERS MANUAL, ADINA Engineering Report AE 81-1, Watertown. Massachusetts, September 1981.

2. ADINA Engineering

ADINA-PLOT: A PROGRAM FOR DISPLAY OF INPUT AND OUTPUT DATA USING ADINA, ADINA Engineering Report AE 83-3, Watertown, Massachusetts, May 1983.

- 3. ADINA Engineering ADINA SYSTEM THEORY AND MODELING GUIDE, ADINA Engineering Report AE 83-4, Watertown, Massachusetts, September 1983.
- 4. Aluminum Company of America ALCOA STRUCTURAL HANDBOOK-A DESIGN MANUAL FOR ALUMINUM, Pittsburgh, Pennsylvania, 1960.
- 5. American Association of State Highway and Transportation Officials STANDARD SPECIFICATIONS FOR HIGHWAY BRIDGES, 13th Ed., AASHTO, Washington, D. C., 1983.
- 6. Bathe, Klaus-Jürgen FINITE ELEMENT PROCEDURES IN ENGINEERING ANALYSIS, Prentice-Hall, Englewood Cliffs, New Jersey, 1982.
- Bathe, K. J., Wilson, E. L., and Peterson, F. E. SAP IV: A STRUCTURAL ANALYSIS PROGRAM FOR STATIC AND DYNAMIC RESPONSE OF LINEAR SYSTEMS, University of California, Berkeley, June 1973, revised April 1974.
- 8. Combined Arms and Services Staff School, U. S. Army COMBINED ARMS OPERATIONS, Fort Leavenworth, Kansas, 1985.
- 9. Cook, R. D. and Young, W. C. ADVANCED MECHANICS OF MATERIALS, Macmillan, New York, 1985.
- 10. Gallagher, Richard H. FINITE ELEMENT ANALYSIS FUNDAMENTALS, Prentice-Hall, Englewood Cliffs, New Jersey, 1975.
- 11. Generic Software GENERIC CADD-LEVEL 2 OPERATOR'S MANUAL, Redmond, Washington, 1987.
- 12. Headquarters, Department of the Army FM 5-100 ENGINEER COMBAT OPERATIONS, Washington, D. C., 1979.

13. Hrennikoff, A.

SOLUTION OF PROBLEMS OF ELASTICTY BY THE FRAMEWORK METHOD, Trans. ASME, Journal of Applied Mechanics, Vol. 8, No. 4, Dec 1941, pp. A-169-175.

14. Hull, Derek

AN INTRODUCTION TO COMPOSITE MATERIALS, Cambridge University Press, Cambridge, 1985.

15. Kostem, C. N.

USER'S MANUAL FOR PROGRAM SPLT (Version 1.0), A PROGRAM TO PLOT THE FINITE ELEMENT MESH OF PROGRAMS SOLID SAP AND SAP IV, Fritz Engineering Laboratory Report No. 400.29, Lehigh University. Bethlehem, Pennsylvania, January 1985.

- 16. Laible, J. P. STRUCTURAL ANALYSIS, Holt Rinehart and Winston, New York, 1985.
- 17. Lotus Development Corp. LOTUS 1-2-3 USER MANUAL, Cambridge, Massachusetts, 1986.
- 18. Meyer, Christian

FINITE ELEMENT IDEALIZATION FOR LINEAR ELASTIC STATIC AND DYNAMIC ANALYSIS OF STRUCTURES IN ENGINEERING PRACTICE. American Society of Civil Engineers, New York, 1987.

- 19. Norris, C. H., Wilbur, J. B., and Utku, S. ELEMENTARY STRUCTURAL ANALYSIS, McGraw-Hill, New York 1977
- 20. Office of the Chief of Staff, U. S. Army THE ARMY OVERVIEW 1988, Washington, D. C., 1988.
- 21. Paperback Software International VP-GRAPHICS-PRESENTATION GRAPHICS AND DRAWING SYSTEM Berkeley, California, 1987.
- 22. Polakowski, N. H. and Ripling, E. J. STRENGTH AND STRUCTURE OF ENGINEERING MATERIALS, Press -Hall, Englewood Cliffs, New York, 1966.
- 23. U. S. Army Belvoir Research, Development, and Engineering Center LIGHT VEHICLE/FOOT BRIDGE CONSTRUCTION DRAWINGS, BRITE Fort Belvoir, Virginia, 1988.
- 24. U. S. Army Belvoir Research, Development, and Engineering Center TRILATERAL DESIGN AND TEST CODE FOR MILITARY BRIDGING AND GAP CROSSING EQUIPMENT (Federal Republic of Germany, United Kingdom, United States of America), BRDEC, Ft. Belvoir, Virginia, 1986.
- 25. Weeton, J. W., Peters, D. M., and Thomas, K. L. ENGINEERS' GUIDE TO COMPOSITE MATERIALS, American Society for Metals, Metals Park, Ohio, 1987.

APPENDIX A. BRIDGE MODEL VERIFICATION

A.1 Purpose

The purpose of this appendix is to present the manual solutions used for verification of the Bridge Models 1 and 2. Two simple analytical models are developed for the manual solutions. These models define upper and lower bounds for the deflections computed in the finite element analyses. The upper and lower bound solutions are compared with the finite element solution in Section A.4.

A.2 Upper Bound Solution

The upper bound solution is performed by modeling the LV/FB as a simplified. two-dimensional, statically determinate truss. A 2.75 kip concentrated load is applied at midspan. This load is equivalent to a 5.5 kip vehicle tire load applied to the full three-dimensional structure. Vertical deflection at midspan is calculated, using the method of virtual work. Maximum stresses in the top and bottom chords are calculated, using elementary mechanics of materials. Because the structure is modeled as a truss, all joints are assumed to be pinned, and all members are assumed to carry axial load only.

The analytical model used for the upper bound solution is shown in Figure A : The model is a statically determinate plane truss. Joint numbers are designated for reference. The general configuration and overall dimensions are identical to those of the actual LV/FB. However, several minor modifications have been made to the model, so that it can be analyzed as a statically determinate truss. Six uprights have been omitted from the outer end of each ramp bay, and two uprights have been relocated to the points where the center bay and ramp bays are connected. Without these changes, the pin-jointed structure would be statically unstable. The diagonal cable braces which would be in compression for this loading condition have also been omitted, as they are in the finite element analyses.

The virtual work expression used for calculation of midspan deflection is

$$(1 \text{ kip})(\delta) = \sum (F_Q)_i \left(\frac{F_P L}{A E}\right)_i$$
(A.1)

where

 δ = midspan deflection $F_Q^{=}$ axial force in member *i* due to a 1 kip virtual force applied vertically downward at midspan $F_{P}^{=}$ axial force in member *i* due to the 2.75 kip load applied at midspan L = length of member *i* A = cross sectional area of member *i* E = modulus of elasticity of member *i*.

The solution is presented in Table A.1. The computed midspan deflection is 6.587 inches.

From elementary mechanics of materials, normal stress, σ , in a truss member is given by

$$\sigma = \frac{F_P}{A}.$$
 (A.2)

From the computed axial forces, F_P , in members I1-J1 and I2-J2, maximum stresses are determined to be -17.86 ksi (compression) in the top chord and +16.64 ksi (tension) in the bottom chord.

A.3 Lower Bound Solution

The lower bound solution is performed by modeling the LV/FB as a twodimensional, nonprismatic beam. A 2.75 kip concentrated load is applied at midspan. Vertical deflection at midspan is calculated, using the method of virtual work. Normal stress in the top and bottom chords at midspan is calculated, using elementary mechanics of materials. Because the entire solution is based on elementary beam theory, plane sections are assumed to remain plane, and shear distortions are neglected.

The analytical model used for the lower bound solution is shown in Figure A.2. The general configuration and overall dimensions are identical to those of the actual LV/FB. However, the cross section of the beam model consists only of one top chord and one bottom chord. Two typical cross sections are indicated—Section A-A in the center bay and Section B-B at the end of the span. The flexural moment of inertia, I, at each of these sections is shown. Variation of I between these two extremes can be approximated as a parabolic function of x. Thus, for one half of the length of the beam,

$$I(x) = 1.1687 + 0.006829x^{2} \text{ (for } 0^{"} \le x \le 137")$$
(A.3a)

$$I(x) = 129.35$$
 (for 137" $\le x \le 220$ "). (A.3b)

I(x) is only defined for half of the beam because the model is symmetrical about midspan.

The virtual work expression used for calculation of midspan deflection is

$$(1 \text{ kip})(\delta) = \int_{\mathbf{L}} \frac{\mathbf{m}M}{\mathbf{E}\mathbf{I}} \, d\mathbf{x}$$
(A.4)

where

 $\delta = \text{midspan deflection}$

m = bending moment in the beam due to a 1 kip virtual force applied vertically downward at midspan

- M = bending moment in the beam due to the 2.75 kip load applied at midspan
- E = modulus of elasticity of the beam = 10295 ksi for Aluminum 7005
- I = flexural moment of inertia of the beam.

Both m and M are linear functions of x. From elementary statics, they are determined

to be

$$m(x) = \frac{x}{5}$$
 (for 0" $\le x \le 220$ ") (A.5a)

$$M(x) = 1.375x \text{ (for } 0^{n} \le x \le 220^{n}\text{)}. \tag{A.5b}$$

Expressions for m(x) and M(x) are only defined for half of the beam because the model is symmetrical about midspan.

Substituting Equations (A.3) and (A.5) into Equation (A.4) yields

$$(1 \text{ kip})(\delta) = 2 \left[\int_{0}^{137} \frac{(1.375 \text{x}) \left(\frac{\text{x}}{2}\right)}{(10295)(1.1687 + 0.006829 \text{x}^2)} \, d\text{x} + \int_{137}^{220} \frac{(1.375 \text{x}) \left(\frac{\text{x}}{2}\right)}{(10295)(129.35)} \, d\text{x} \right] \quad (A.6)$$

Note that the symmetry of the beam is taken into account by evaluating the virtual work expression for $\frac{L}{2}$ and multiplying the result by 2. When the expression is simplified, midspan deflection is found to be 5.082 inches.

Normal stress, σ , is determined from the flexure formula,

$$\sigma = \frac{M_{max} c}{I_m} \tag{A.7}$$

where

$$M_{max} =$$
 bending moment at midspan = 302.5 kip-in
c = vertical distance from the neutral axis to the centroid of the
top or bottom chord at midspan = ∓ 7.5 inches
 I_m = flexural moment of inertia at midspan = 129.35 in⁴.

Using this expression, normal stress in the beam at midspan is found to be -17.54 ksi (compression) at the centroid of the top chord and +17.54 ksi (tension) at the centroid of the bottom chord.

A.4 Comparison of Results

The results of the upper bound solution, lower bound solution, and finite element solution are compared in Table A.2. Midspan deflections and normal stresses in the top and bottom chords at midspan are provided. The finite element solution is performed with Bridge Models 1 and 2. Two 2.75 kip concentrated loads are applied at midspan, one at each of the two top chords. This loading condition is statically equivalent to the single 2.75 kip load applied to the two-dimensional truss and beam models.

Two conclusions can be drawn from the results presented in Table A.2:

(1) As expected, the midspan deflection computed in the finite element solution is greater than that of the lower bound solution and less than that of the upper bound solution.

(2) Computed normal stresses agree reasonably well for all three cases.

MEMBER		Fe	L-	Α	E	FPL	Fo	$(\mathbf{F}_{O})\left(\frac{\mathbf{F}_{P}\mathbf{L}}{\mathbf{F}_{D}}\right)$
		(kips)	(inches)	(in ²)	(ksi)	A L	(kips)	· · · (AE)
Top	A1-81	+12.633	97.580	1.129	10295	-0.106	-4.594	0.487
Chords	B1-C1	-12.633	10.060	1.129	10295	-0.011	-4.594	0.050
	C1-D1	-12.633	11.070	1.129	10295	-0.012	-4.594	0.055
	D1-E1	-12.633	19.110	1.129	10295	-0.021	-4.594	0.095
	E1-F1	-14.666	23.000	1.129	10295	-0.029	-5.333	0.155
	F1-G1	-16.041	15.000	1.129	10295	-0.021	-5.833	0.121
	G1-H1	-17.416	15.000	1.129	10295	-0.022	-6.333	0.142
	H1-I1	-18.791	15.000	1.129	10295	-0.024	-6.833	0.166
	11-J1	-20.166	15.000	1.129	10295	-0.026	-7.333	0.191
	J1-K1	-20.166	15.000	1.129	10295	-0.026	-7.333	0.191
	K1-L1	-18.791	15.000	1.129	10295	-0.024	-6.833	0.166
	L1-M1	-17.416	15.000	1.129	10295	-0.022	-6.333	0.142
	M1-N1	-16.041	15.000	1.129	10295	-0.021	-5.833	0.121
	N1-01	-14.666	23.000	1.129	10295	-0.029	-5.333	0.155
	01- P1	-12.633	19.110	1.129	10295	-0.021	-4.594	0.095
	P1-Q1	-12.633	11.070	1.129	10295	-0.012	-4.594	0.055
	Q1-R1	-12.633	10.060	1.129	10295	-0.011	-4.594	0.0 50
	R1-51	-12.633	97.580	1.129	10295	-0.106	-4.594	0.487
Bottom	A1-82	12.558	97.000	1.129	10295	0.105	4.567	0.479
Chords	B2-C2	12.558	10.000	1.129	10295	0.011	4.567	0.049
	C2-D2	12.558	11.000	1.129	10295	0.012	4.567	0.054
	D2-E2	12.558	19.000	1.129	10295	0.021	4.567	0.094
	E2-F2	12.558	23.000	1.129	10295	0.025	4.567	0.113
	F2-G2	14.666	15.000	1.129	10295	0.019	5.333	0.101
	G2-H2	16.041	15.000	1.129	10295	0.021	5.833	0.121
	H2-12	17.416	15.000	1.129	10295	0.022	6.333	0.142
	12-J2	18.791	15.000	1.129	10295	0.024	6.833	0.166
	J2-K2	18.791	15.000	1.129	10295	0.024	6.833	0.166
	K2-L2	17.416	15.000	1.129	10295	0.022	6.333	0.142
	L2-M2	16.041	15.000	1.129	10295	0.021	5.833	0.121
	M2-N2	14.666	15.000	1.129	10295	0.019	5.333	0.101
	N2-02	12.558	23.000	1.129	10295	0.025	4.567	0.113
	02-P2	12.558	19.000	1.129	10295	0.021	4.567	0.084
	P2-Q2	12.558	11.000	1.129	10295	0.012	4.547	0.054
	Q2-R2	12.550	10.000	1.129	10295	0.011	4.567	0.049
	R2-52	12.550	97.000	1.129	10295	0.105	4.567	0.479
*Uprights	F1-F2	-1.375	15.000	0.969	10295	-0.002	-0.500	0.001
	G1- G2	-1.375	15.000	0.969	10295	-0.002	-0.500	0.001
	H1-H2	-1.375	15.000	0.969	10295	~0.002	-0.500	0.001
	11-12	-1.375	15.000	0.969	10295	-0.002	-0.500	0.001
	J1-J2	-2.750	15.000	0.969	10295	-0.004	-1.000	0.004
	K1-K2	-1.375	15.000	0.969	10295	-0.002	-0.500	0.001
	L1-L2	-1.375	15.000	0.969	10295	-0.002	-0.500	0.001
	M1-M2	-1.375	15.000	0.969	10295	-0.092	-0.500	0.001
	N1-N2	-1.378	15.000	0 969	10295	-0.002	-0.500	0.001
Diagonal	E1-#2	2.517	27.460	0.012	29000	0.194	0.915	0.178
Cable	F1-02	1.945	21.210	0.012	29000	0.110	0.7 07	0.082
Braces	G1-H2	1.945	21.210	0.012	29000	0.116	0.707	0.082
	H1-12	1.945	21.210	0.012	29000	0.116	0.707	0.062
	11-32	1.945	21.210	0.012	29000	0.116	0.707	0.082
	J2-K1	1.945	21.210	0.012	29000	0.116	0.707	0.082
	K2-L1	1.945	21.210	0 012	29000	0.116	0.707	0.082
	L2-M1	1.945	21.210	0 012	29000	0.116	0.707	0.082
	M2-N1	1.945	21.210	0.012	29000	0.116	0.707	0.082
	N2-01	2.517	27.460	0.012	29000	0.194	0.915	0.178
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-					<u></u> (Fq	NATE		0.387
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Table A.1. Calculation of Midspan Deflection for the Upper Bound Solution

Table A.2. Comparison of Results of Upper Bound Solution, Lower Bound Solution, and Finite Element Solution

	Upper Bound Solution [Truss] [Model]	Lower Bound Solution [Beam] Model]	Finite Element Solution Bridge Models 1 & 2
Midspan Deflection	6.587 inches	5.082 inches	5.371 inches
Top Chord Normal Stress	-17.86 ksi	-17.54 ksi	-16.86 ksi
Bottom Chord Normal Stress	+16.64 ksi	+17.54 ksi	+16.62 ksi



Figure A.1. Analytical Model Used for the Upper Bound Solution



Figure A.2. Analytical Model Used for the Lower Bound Solution

APPENDIX B. MEMBRANE DECK MODEL VERIFICATION

B.1 Purpose

The purpose of this appendix is to present the manual solutions used for verification of Membrane Deck Models 1 and 2. A relatively crude analytical model is developed for the manual solutions. This model is used to calculate upper and lower bounds for the deflections computed in the finite element analyses. The upper and lower bound solutions are compared with the finite element solution in Section B.3.

B.2 Upper and Lower Bound Solutions

In both the upper and lower bound solutions, the composite membrane deck is modeled as two bands of unidirectional fibers, one longitudinal and one transverse. Cross sectional properties of the bands are defined such that they are consistent with the section properties and fiber orientation of MEMBRANE A. Upper and lower bounds are established by varying the width of the transverse band. A 5.5 kip load is applied at midspan. Maximum deflection and load distribution to the top chords are computed, using the Rayleigh-Ritz method. Because it relies on an assumed deflected shape, the Rayleigh-Ritz method provides only an approximate solution. Moreover. the analytical model used is relatively crude. Thus this solution can be regarded as only a rough approximation of the behavior of the actual membrane.

The analytical model used in the upper and lower bound solutions is shown in Figure B.1. The overall dimensions are consistent with those of Membrane Deck Model 1. The membrane itself is represented by longitudinal and transverse bands of unidirectional fibers, as indicated. The vehicle tire load, P, is applied at the intersection of the two bands. In effect, these bands represent assumed load paths.

Applied vehicle tire loads are assumed to be transmitted primarily in the longitudinal and transverse directions, from the point of application to the supports (the top chords and deck end plates). This assumption is reasonable for MEMBRANE A, because that membrane configuration has no diagonally oriented fibers.

Note that, for the upper bound solution, the width of the transverse band is 4.6 inches. This value is used because it is the approximate longitudinal dimension of the MLC 8 tire footprint, if the shape of the footprint is assumed to be rectangular. Thus the upper bound solution assumes that the load which is transmitted laterally from the tire footprint to the top chords *does not spread longitudinally as it is transmitted*. The lower bound solution, with a 12.0 inch wide transverse band, allows for significant longitudinal spreading of transmitted loads. Because a larger portion of the membrane is assumed to be active in carrying load in this case, computed deflection is expected to be somewhat smaller than in the upper bound solution.

Sections A-A and B-B show the assumed shape of the deflected membrane decay For simplicity, a piecewise linear deflected shape is used in both the longitudinal and transverse directions. A single displacement parameter, δ , defines the magnitude of the maximum deflection.

The following procedure is used to perform the solution:

(1) An expression for the total strain energy, U, is developed for the deflected membrane deck. This expression is in terms of the displacement parameter, δ .

(2) An expression for the *potential of the loads*, V, is developed for the deflected membrane deck. This expression is also in terms of δ .

(3) An expression for the total potential, $\Pi = U + V$, is developed.

(4) The total potential is minimized with respect to the displacement parameter

and the resulting expression is solved for δ .

Strain is assumed to be uniform throughout each of the two bands which constitute the analytical model. Thus the strain energy, U, for a single band is given by

$$\mathbf{U} = \frac{\mathbf{A}\mathbf{E}\mathbf{L}}{2} \,\epsilon^2 \tag{B.1}$$

where

A = cross sectional area of the composite fibers in the band

E = modulus of elasticity of the composite fibers in the band

L = length of the band

 ϵ = elastic strain in the composite fibers.

The elastic strain, ϵ , can be determined from

$$\epsilon = \frac{L_f - L_i}{L_i} \tag{B.2}$$

where

 $L_f =$ final length of the band, in the deflected position $L_i =$ initial length of the band, in the undeflected position.

 L_i is equal to 36 inches for the transverse band and 150 inches for the longitudinal band, as is indicated in Figure B.1. L_f is a function of the displacement parameter. \uparrow From the geometry of the assumed deflected shape of the membrane deck, L_f is determined to be

$$L_f = 2\sqrt{144+\delta^2} + 12$$
 (for the transverse band) (B. 44)

$$L_f = 2 \sqrt{5625 + \delta^2}$$
 (for the longitudinal band). (B. 9)

Substituting Equations (B.2) and (B.3) into Equation (B.1), the total strain energy for both bands is found to be

U = 18 A_iE
$$\left[\frac{\sqrt{144+\delta^2}}{18} - \frac{2}{3}\right]^2 + 75 A_iE \left[\frac{\sqrt{5625+\delta^2}}{75} - 1\right]^2$$
 (B.4)

where

 $A_t = cross$ sectional area of the transverse band $A_l = average cross sectional area of the longitudinal band.$

The vehicle tire load, P, is applied at the same location as the displacement parameter, δ , is measured. Thus the tire load displaces by an amount δ , and the potential of the loads, V, is simply

$$\mathbf{V} = -\mathbf{P}\delta \tag{B.5}$$

Combining Equations (B.4) and (B.5), the total potential, II, is

$$\Pi = U + V$$

$$= 18 A_{t} E \left[\frac{\sqrt{144 + \delta^{2}}}{18} - \frac{2}{3} \right]^{2} + 75 A_{t} E \left[\frac{\sqrt{5625 + \delta^{2}}}{75} - 1 \right]^{2} - P\delta. \quad (B.6)$$

The Rayleigh-Ritz method requires that the total potential be minimized with respect to the displacement parameter. This is accomplished by taking the first derivative of II with respect to δ , and setting the resulting expression equal to zero. The result is

$$\frac{d\Pi}{d\delta} = 2E\delta \left[A_t \left(\frac{1}{18} - \frac{2}{3\sqrt{144 + \delta^2}} \right) + A_t \left(\frac{1}{75} - \frac{1}{\sqrt{5625 + \delta^2}} \right) \right] - P = 0$$
(B.7)

While this expression cannot be solved for δ in closed form, a numerical solution can be obtained, once values are substitued for E, A_t, A_l , and P. For consistency with the

nonlinear finite element analysis of MEMBRANE A, the following values are used:

$$P = 5.5 \text{ kips}$$

$$E = 13500 \text{ ksi}$$

$$A_{i} = 0.12 \text{ in}^{2}$$

$$A_{t} = \begin{cases} 0.023 \text{ in}^{2} \text{ (upper bound)} \\ 0.06 \text{ in}^{2} \text{ (lower bound)}. \end{cases}$$

The upper bound value for A_t corresponds to a 4.6 inch wide transverse band. The lower bound value corresponds to a width of 12.0 inches.

Computed deflections provide one basis for comparison of the results of the manual solutions and the finite element solution. It is also useful to compare the vertical and horizontal distributed loads applied to the top chords by the membrane. (See Section 4.2.3.1.) Once Equation (B.6) is solved for δ , the corresponding distributed loads can be easily computed from statics. The vertical distributed load, w_{ν} (in kips/inch), is given by

$$\mathbf{w}_{v} = \left[\frac{\delta}{\sqrt{144 + \delta^{2}}}\right] \left(\frac{\epsilon \mathbf{E} \mathbf{A}_{t}}{\mathbf{b}}\right) \tag{B.8}$$

where b is the width of the transverse band in inches and ϵ , the elastic strain, is computed from Equation (B.2). Similarly, the horizontal distributed load, w_h (in kips/inch), is

$$\mathbf{w}_{h} = \left[\frac{12}{\sqrt{144+\delta^{2}}}\right] \left(\frac{\epsilon \mathbf{E} \mathbf{A}_{t}}{\mathbf{b}}\right). \tag{B.9}$$

B.3 Comparison of Results

The finite element solution is performed with Membrane Deck Model 1, using the fiber configuration of MEMBRANE A. The MLC 8 critical vehicle tire load (5.5 kips) is applied at the center of the deck. Computed maximum deflections from the finite

element solution and the two manual solutions are as follows:

Upper bound solution: 3.62 inches

Finite element solution: 3.51 inches

Lower bound solution: 2.62 inches

As expected, the finite element solution is between the upper and lower bounds.

Computed vertical and horizontal load distributions are compared in Figures B.2 and B.3, respectively. Again, the finite element solution is bounded by the two manual solutions in both figures.

Given the crudeness of the analytical model used for the upper and lower bound solutions, the three solutions actually agree quite well; more importantly, the differences between them are fully consistent with the assumptions used in developing the analytical model.



Figure B.1 Analytical Model Used for Upper and Lower Bound Solutions


Figure B.2. Comparison of Computed Vertical Load Distribution for Upper Bound, Lower Bound and Finite Element Solutions



Figure B.3. Comparison of Computed Horizontal Load Distribution for Upper Bound, Lower Bound and Finite Element Solutions

APPENDIX C. RELATIVE SEVERITY OF LOADS

C.1 Purpose

The purpose of this appendix is to present an analysis of the relative severity of loads for the LV/FB. Mud load, wind load, and braking load are considered. The basis for determination of relative severity is maximum computed normal stress in the top chords. For each load type, top chord stresses are calculated via a simple analytical model. Results are summarized and compared in Section C.6.

C.2 Analytical Model

Figure C.1 shows the analytical model used for determination of the relative severity of loads. Plan and elevation views are provided, as well as a typical cross section of the center bay. Coordinate axes are indicated. The LV/FB superstructure is idealized as a nonprismatic beam, simply supported in both the xy- and xz- planes. The cross section of the beam consists of the top and bottom chords, as indicated in Section A-A. Cross sectional area and flexural moments of inertia are indicated.

C.3 Mud Load

Mud load is specified as 15.65 pounds/ft² (0.0001087 kips/in²), distributed over the entire surface of the deck. (See Section 5.2.3.) From elementary statics, the maximum bending moment, M_{max} , caused by this distributed load is given by

$$M_{max} = \frac{w L^2}{8}$$
(C.1)

where

 w = two-dimensional distributed load = 0.004022 kips/in (for mud load applied across the entire 37 inch wide deck)
L = span length = 440 inches. The calculated maximum moment is 97.33 kip-inches. From elementary mechanics of materials, maximum normal stress, σ , in the top chords is given by

$$\sigma = \frac{M_{max} c}{I}$$
(C.2)

where

$$c = -9$$
 inches
I = I₂ = 258.7 in⁴.

From Equation (C.2), maximum normal stress in the top chords at midspan is found to be -3.39 ksi (compression).

C.4 Wind Load

In this analysis, the only significant wind loads are those applied to the crossing vehicle. These loads are transmitted to the deck of the LV/FB through the tires of the vehicle. Thus it is necessary to identify the position of the design vehicle which causes maximum moments in the analytical model.

The MLC 7 vehicle load position which causes maximum moments in the analytical model is shown in Figure C.2. The three applied loads are designated as P; they represent vehicle tire loads, vertical wind loads, or horizontal wind loads. (They can represent horizontal loads because the analytical model is simply supported in xzplane, as well as the xy-plane.) The vehicle is positioned such that the point midway between the center tire and the center of gravity of the three loads is at midspan. This load position produces the largest possible bending moment directly under the center tire [19]. The figure includes a moment diagram for this loading condition. The maximum moment, Mmax (in kip-inches), is given as

$$M_{max} = 247.0 P$$
 (C.3)

where P is the applied load, in kips.

In Section 5.2.4 wind load for the MLC 7 vehicle is determined to consist of a 0.261 kip vertical load and a 0.163 kip horizontal load applied to the deck at each tire position. Figure C.3 shows the wind loads applied to the cross section of the analytical model. Both loads are applied at the level of the deck, as indicated at the top of the figure. Statically equivalent forces and moment acting at the centroidal axis of the beam are shown below. This diagram suggests that wind load produces three principal effects in the analytical model:

(1) Bending in the xy-plane due to the 0.261 kip vertical force. This bending causes compressive stresses in both top chords.

(2) Bending in the xz-plane due to the 0.163 kip horizontal force. This bending causes compressive stresses in the top chord on the upwind side and tensile stresses on the downwind side.

(3) Twisting about the x-axis due to the 1.471 kip-inc.: moment. The torsional moment causes both shear stresses (due to St. Venant torsion effects) and normal stresses (due to warping effects). However, the simple analytical model is not capable of accurately predicting these effects in the actual structure. Thus stresses due to the torsional moment are not considered in this analysis.

From (1) and (2), it can be concluded that the maximum normal stress in the top chords must be a compressive stress, occurring on the upwind side. Furthermore, it is clear that the maximum stress must occur at the top of the top chord on the upwind side, as indicated in Figure C.3. Maximum stress does not occur at the upwind

side of the top chord, because the horizontal force is smaller than the vertical force, and I_y is much larger than I_z .

Though warping normal stresses are not considered, it is worth noting that the effect of warping would be to decrease the compressive stress in the top chord on the upwind side. Thus it is conservative to neglect this effect.

From Equation (C.3), the maximum bending moments due to the vertical and horizontal wind loads are found to be 64.47 kip-inches and 40.36 kip-inches, respectively. From Equation (C.2), the corresponding normal stresses at the top of the top chord on the upwind side are computed as -2.24 ksi and -0.48 ksi. The total normal stress due to wind load is -2.72 ksi.

C.5 Braking Load

In Section 5.2.5, the braking load for the MLC 7 vehicle is determined to be a 1.313 kip longitudinal force, applied by each tire. These forces are applied at the level of the deck.

Figure C.4 shows the application of braking load to the analytical model. Line MLC 7 vehicle is positioned with the middle tire directly over the inner end of a ram, bay, as indicated. This position, determined by trial-and-error, results in maximum normal stresses in the top chords. Because the longitudinal braking forces are applied at the level of the deck, they have the effect of applying longitudinal forces and concentrated moments at the centroidal axis, as indicated in the free body diagram Note that the moment caused by the rear wheel is smaller than the other two, because this wheel is positioned on the ramp bay. From the moment and axial force diagrams it is clear that maximum normal stress in the top chords must occur directly below the front tire of the MLC 7 vehicle. The maximum normal stress, σ , is given by

$$\sigma = \frac{F_{max}}{A} + \frac{M_{max} c}{I}$$
(C.4)

where

 F_{max} = maximum axial force = -3.949 kips A = cross sectional area = 4.511 in² M_{max} = maximum moment = 13.03 kip-inches c = -9 inches I = I_s = 258.7 in⁴

Maximum normal stress due to braking loads is found to be -1.33 ksi.

C.6 Comparison of Results

In Sections C.3 through C.5, maximum normal stresses occurring in the top chords of the LV/FB for mud, wind, and braking loads are calculated. The results are summarized as follows:

Mud load: -3.39 ksi Wind load: -2.72 ksi Braking load: -1.33 ksi

It is concluded that mud load has the most severe effect on top chord normal stresses. Wind load is ranked second, and braking load is least severe. This conclusion is strengthened by the significant differences between all three calculated values. Any error which might have been introduced by using the simple analytical model is not likely to change the relative severity ranking of the three load types.



Figure C.1. Analytical Model Used for Determination of Relative Severity of Loads

LOAD POSITION



MOMENT DIAGRAM



Figure C.2. MLC 7 Vehicle Load Position Which Causes Maximum Moments in the Analytical Model



Figure C.3. Wind Loads Applied to the Cross Section of the Analytical Model

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MLC 7 VEHICLE POSITION



FREE BODY DIAGRAM



AXIAL FORCE DIAGRAM



