Borrower:

Note
Title from cover.
TL 950 .S583
Location SCIENCE 2nd FLOOR
LIB. HAS 25(1993)-34(2002)
Latest Received :
2001-02 33-34
LOCATION
CALL #
STATUS

157.182.199.203

Record 242 of 278
ILL pe

Record 242 of 278

CAN YOU SUPPLY ? YES NO COND FUTUREDATE
:ILL: 9113858 :Borrower: WVU :ReqDate: 20030915 :NeedBefore: 20031015
:Status: IN PROCESS 20030915 :RecDate: :RenewalReq:
:OCLC: 28528320 :Source: OCLCILL :DueDate: :NewDueDate:
:Lender: *AZS,SCT,MUS,OKU,UCW
:TITLE: Journal of advanced materials /
:IMPRINT: Covina, CA : The Society, c1993-
:ARTICLE: Kosmatka, J.B.; Policelli, F.J.: Development of the DARPA/BIR Composite Army Bridge: Phase I accomplishments
:VOL: v 31 :NO: n 3 :DATE: July 1999 :PAGES: p 23-36
:VERIFIED: <TN:61372>OCLC ISSN: 1070-9789 [Format: Serial]
:PATRON: liang, ruifeng
:SHIP TO:
ILLWEST VIRGINIA UNIVERSITY
EVANSDALE LIBRARY
P.O. BOX 6105
EVANSDALE DR.
MORGANTOWN, WV 26506-6105

:BILL TO: SAME

:SHIP VIA: ARIEL 157.182.199.203 :MAXCOST: $34.00IFM
:COPYRT COMPLIANCE: CCG
:FAX: 304.293.7330
:E-MAIL: illevan@mail.wvu.edu

OCLC Number:

ILLWEST VIRGINIA UNIVERSITY
EVANSDALE LIBRARY
P.O. BOX 6105
EVANSDALE DR.
MORGANTOWN, WV 26506-6105

The Development of the DARPA/BIR Composite Army Bridge: Phase I Accomplishments

J.B. Kosmatka
Department of Applied Mechanics and Engineering Science,
University of California, San Diego, CA

F.J. Policelli
Engineering Consultant,
Salt Lake City, UT

Received 01/20/98; Revised manuscript received 01/30/99

Abstract

The U.S. Army is interested in developing new lightweight short-span mobile bridging systems that will significantly improve their tactical mobility (rapid deployment/retrievals, carry multiple bridges per launcher). Most important, it is required that this bridge weigh and cost less than existing metallic bridges. One concept currently being investigated as part of the DARPA sponsored Bridge Infrastructural Renewal (BIR) Phase I program involves the development of an all Composite Army Bridge (CAB). In this paper, an overview of the CAB development program is presented including: requirements, bridge design, analysis, low-cost fabrication techniques and the experimental testing program. A detailed cost and weight analysis of the current bridge reveals that it will cost 20% less and weigh 25% less than a similar existing metallic (Aluminum) bridge.

Introduction

The U.S. Army is interested in developing new lightweight short-span mobile assault bridging systems. Most of the current bridging systems developed in the 1960s are not capable of carrying many of today's heavier (70-100 ton) wheeled and tracked vehicles, are not serviceable or upgradeable, [1] or are so heavy that they limit the force's mobility. The need for rapidly deployable lightweight bridging remains as important today as ever in order for armored vehicles and support vehicles to accomplish their mission. It has been shown by NATO obstacle plans of Western Europe [2] that through a combination of simple natural features and a coordinated plan of man-made obstacles that the mobility of an entire armored formation can be restricted, channeled, or even blocked. For the defender, the creation of a coordinated obstacle plan is central to forcing the enemy to a prearranged target spot, while at the same time providing security from flanking maneuvers. For example, it was established that in the absence of bridges, 80% of water obstacles cannot be crossed or would prove difficult to cross even with modern water mobile vehicles and/or armored tracked vehicles. In most cases, it was not the depth of the water or the width of the gap, but rather the condition of the bank that stopped the vehicles. In fact, over 92% of the natural gaps in Europe and over 51% of the natural gaps in Southeast Asia are less than 40 feet wide. In addition, almost all man-made obstacles of "tank-traps" are less than 30 feet wide. Thus, in these areas short-span bridging is more important than long-span (assembled) bridging.

A detailed review study was performed to assess the current state of military bridging, worldwide. Single and assembled bridging systems of 15 different countries were reviewed. These countries include: Brazil, China, Czechoslovakia, France, Germany, Italy, Japan, Netherlands, Poland, Russia, Singapore, Sweden, Switzerland, United Kingdom and the United States. Based upon this study it was concluded that:

1. There are only eight different types of single-span bridges on the market, from six different countries, where the bridge length varies from 35 to 60 feet (10.7-18.3 m), the bridge weight varies form 6,000 to 20,000 lbs (2700-9100 kg), and the capacities range from 44,000 to 140,000 lbs (20,000-63,500 kg),

2. There are no composite bridges or even components in commercial existence,

3. Thompson Defense Projects, United Kingdom, manufactures a single-span Aluminum bridge (model: Vickers #12) with an overall length of 44 feet (13.5 m) that is able to cross a maximum 12 meter operational gap has a nominal weight of 12,000 lb (5440 kg), has a maximum depth of 28 inch (0.71 m), has a maximum load capacity of a fully loaded M1-A1 tank (150,000 lb, 68,000 kg), and their launcher can carry two bridges simultaneously, and,

4. The United States does not have a manufacturer for mechanical military bridges.

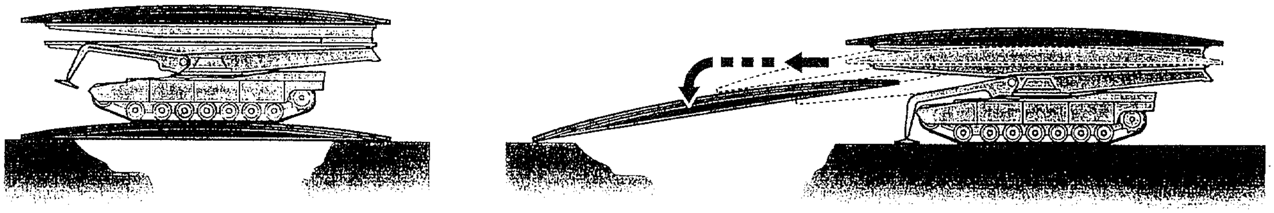

Figure 1. Launching schemes for CAB.

This information was used to define the critical "design/performance metrics" for the proposed technology demonstration Composite Assault Bridge (CAB). The CAB was required to have a lower weight (9000-11,000 lb., 4100-5000 kg) and a lower production/sales cost (based upon a 100 (or more) unit order), while maintaining the same operational envelope. [3] Also it has the ability to carry tow CAB's on an existing launcher (U.S. Army specified General Dynamics M1-A1 launch vehicle for the Heavy Assault Bridge (HAB/Wolverine)) which doubles the range, see Figure 1. Alternatively, both bridges could be partially stacked to cross a complicated longer single gap. Due to the large size of the General Dynamics launcher and the firm (4 meter) Western European underpass height limit, the resulting CAB must have a maximum height of less than 25.6 inches (0.65 m). This is significantly lower than the 28 inch (0.71 m) maximum depth of the existing metallic Vickers #12 bridge. Advanced polymeric composite materials (PCMs) are the only option for producing a minimum depth low-weight bridge to support a Military Load Class (MLC) vehicle of the 70 to 100 ton weight range (63,000-100,000 kg). An example of an MLC-70 vehicle is the M1A1-Abrams tank and an example of an MLC-110 vehicle is the 110 ton Heavy Equipment Transport (HET). Recent attempts to develop a metallic bridge of this minimum 24 inch (0.61 m) depth would require steel in both the upper (deck) and lower (tension rails) extremes, thus leading to a severe overweight condition. The current CAB system is of interest to the Marines where helicopter "bridge drop-ins" are battle field scenarios and also of interest for civil emergencies (floods, earthquakes) where quick bridge replacement is needed to restore the infrastructure.

The overall form is dictated by the need for low-weight, transportability, and quick launcher-based placement without direct human contact. The simple form is characterized by tow parallel treadways (planks) that are connected by separator bars. These bars are detachable so that the individual treadways can be stacked for storage or transportation. Each treadway has a flat, but open, bottom surface for crossing gaps form zero to maximum length. The upper (roadway) surface is a constant radius camber (see Figure 2) form to maximize the bending stiffness without producing highly loaded corners or introducing mechanical joints. This upper surface is unique in comparison to metallic bridges which are defined as wither tow flat faceted surfaces or three flat faceted surfaces (up-ramp, flat, down-ramp), where the facet corners experience large structural loads.

It is obvious that using composite materials will improve the bridge performance (load carrying capability per poind of bridge weight) and launcher mobility (lightweight bridging), but it must be cost-effective and the design must be optimized for composites, not metallics. For example, Army sponsored studies in the 1980s [4,5] attempted to use composites as lightweight replacement components for upgrading existing metallic bridges. These studies, replaceable roadway deck panels and tension chord overlays, exposed the weaknesses of composites (instead of their strengths) by producing costly failures as a result of unplanned compression loadings, abrasion, and/or inadequate bolted joints. Moreover, these components were not cost effective, since they relied on expensive aerospace manufacturing approaches (filament winding, prepreg materials and autoclave cures). Instead, the current CAB development program relies upon recent advances in

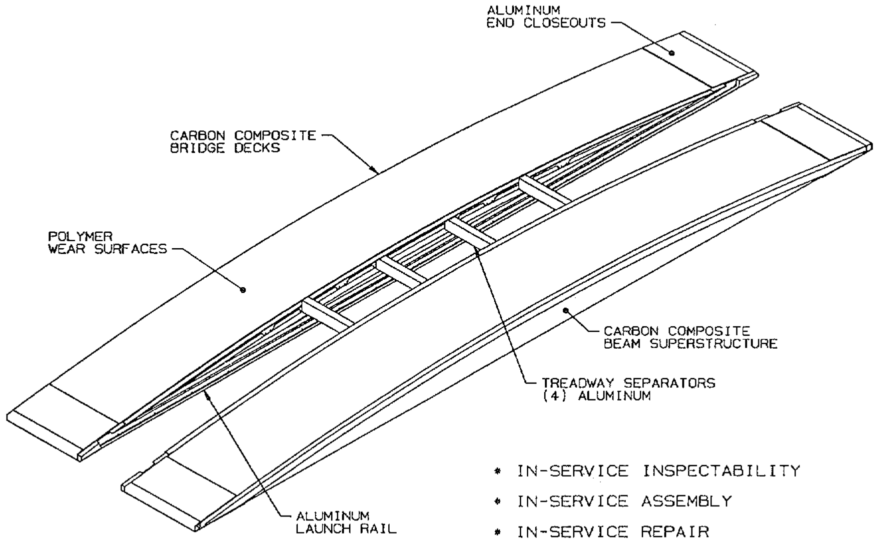

Figure 2. Overall composite assault bridge (CAB) design.

low-cost composite manufacturing processes, like vacuum assisted resin transfer molding (VARTM) and/or SCRIMP, combined with a conservative structural design/analysis approach that is tailored to the manufacturing process limits. SCRIMP is a patented semi-automated extension of the vacuum assisted resin transfer molding (VARTM) process. In this process, the structure is laid-up using dry stitched fabric onto low-cost tooling, vacuum bagged, and then resin infused, where the resin cure can be either room-temperature or elevated-temperature.

Requirements

The critical geometric constraints and load envelope was developed using for important military documents.[3,6-8] These requirements can be divided into five classes: General, Geometric, Load, Boundary Conditions and Environment. The *general performance* requirements include:

1. Advanced composite materials,

2. Fully compatible with the existing General Dynamics Land Systems M1-A1 vehicle launcher,

3. Four inch (0.10 m) maximum bridge static displacement from an MLC-70 vehicle,

4. Durable (minimum of 5000 MLC-70 vehicle crossings), and,

5. No folding/locking mechanisms.

The CAB outer *geometric envelope* must have;

1. An overall length of less than 50 feet (<15 meter) and an operational crossing gap span of 39.4 ft (12 meter),

2. A total width of 13.1 feet (4 m) which is composed of two 5 ft (1.55 m) wide treadways separated by a 3.1 ft (0.90 m) center gap,

3. A maximum height of less than 25.6 inch (0.65 m),

4. A maximum curb step of 4.0 inch (10 cm), and,

5. An end-ramp slope of twenty percent.

The *load environment* included the general category and all specific vehicles pertaining to the wheeled and tracked MLC-50, MLC-70 and MLC-110.[3] In addition, added loads include:

1. Vehicle braking/slewing,

2. Bridge dead load,

3. Launching loads,

4. Impact loads,

5. Vehicle eccentricity load factor (1.26) and,

6. Environmental or thermal loads.

A factor of safety of either (1.5) or (1.8) is applied to all loads depending upon if the material properties are calculated based upon aerospace-certified A-basis or B-basis allowable, respectively.[9,10]

The bridge must be able to span a variety of boundary conditions, including;

1. A 20% height difference between the ends,

2. Longitudinal (uphill/downhill) bank slopes of 1:10,

3. Transverse (twisting) bank slopes of 1:20,

4. Irregularities including steps and depressions of up to six inch (15 cm), and,

5. Low soil bearing pressures of 16 lb/in^2 (110 kPa).

The potential bridge *environments*:

1. 0.11lb/in^2 (0.76 kPa) mud/snow/ice loads,

2. 25 mph (56 km/hr) cross wind loads, and,

3. Humidity, solar radiance over temperature extremes from -45°C (-50°F) to 50°C (120°F).

Design Issues

The CAB design is a two parallel treadway system linked using detachable separator bars. Preliminary weight/stiffness/strength trade studies revealed the necessity for a nearly all graphite design coupled with a low-cost manufacturing (VARTM, SCRIMP) approach. Glass was investigated to lower the cost, but at a significant weight penalty. For example, using glass in the roadway deck or tension rails is not feasible, whereas using in the side-walls is potentially possible. Various resins were investigated, but due to the needed strength and fatigue requirements, and elevated temperature (160°F) epoxy (Shell Epon 862 Epicure) with a post-cure was selected.

Each treadway is characterized by:

1. A lower superstructure,

2. A roadway deck,

3. A wear surface,

4. Aluminum end-caps for impact resistance, and,

5. Aluminum launch rails. See Figure 3.

The treadway lower superstructure is a 541 inch (13.7 m) long hull with an arc-like W-shaped cross-section, where the maximum mid-length depth is 21.5 inch (0.55 m) and the upper edge arc has a radius of 1743 inch (44.3 m). The outer arc-like side walls are vertical whereas the inner arc-like side walls are offset 12 inch (0.3 m) from the outer walls and have a constant angle of 62.5 degrees. Thus, the arc-like middle surface between the two angled inner walls has an increasing width that ranges from 13.6 inch (0.35 m) to 36 inch (0.91 m) as one moves from the treadway mid-length to the ends, respectively. The vertical and angled side walls, as well as the middle arc-like surface is composed of six plies of stitched tri-axial [±45/90] graphite (AMOCO T300) fabric (cured laminate thickness = 0.216 inch, 5.50 mm) for maximum compression and buckling stiffness and strength. The tri-axial plies are slit with overlap joints on the three horizontal surfaces so that under vacuum, these plies are

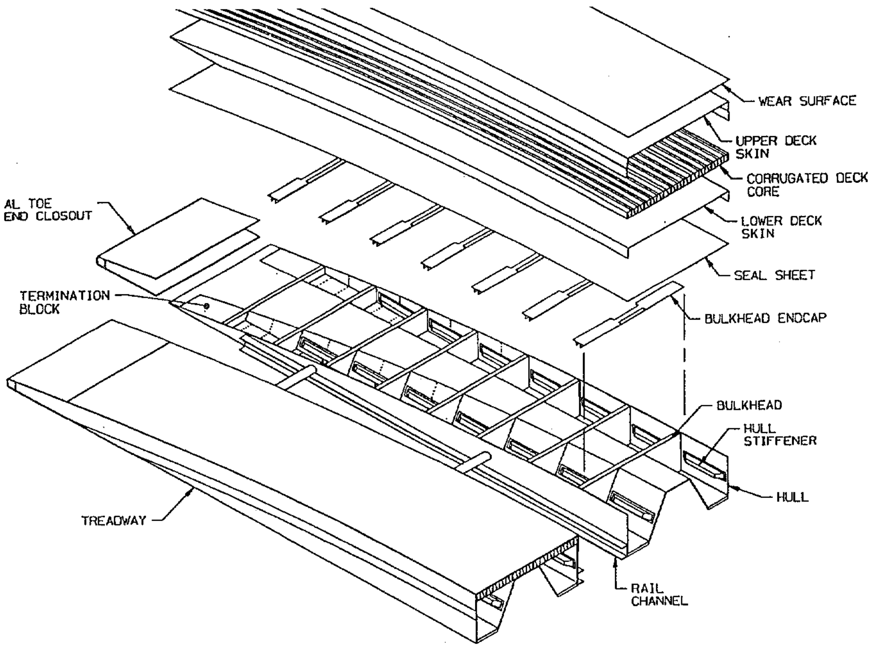

Figure 3. Exploded view of CAB half-length.

free to move and closely match the tight inner corner radii. In the lower-most 12 inch (0.30 m) wide sections, 40 plies of unidirectional (0 degree) (Hexcel AS4-D) graphite are added to the laminate to provide the critical tension component of the treadway bending stiffness. The resulting thickness is 1.18 inch (30mm) in the mid-length portion of this lower-most region. The 40 plies are added in ten four ply through-thickness stitched quilt packs that are alternately placed between the aforementioned six tri-axial layers for better load transfer (i.e., tri-axial fabric, two quilt packs, tri-axial fabric, two quilt packs, tri-axial fabric, etc.). The stitching is done in order to make it easy to handle and more importantly to provide a resin feed path in the SCRIMP process to assist in wetting out the graphite plies. To better improve the shear transfer between the upper deck and lower tension rails at the treadway ends, five quilt ply packs are systematically dropped off over the outer-most 65 inch (1.65 m) length, while simultaneously adding four tri-axial plies over the outermost 135 inch (3.43 m) length.

Seventeen internal bulkheads of varying depths are fabricated separately and secondarily bonded to the lower hull on 30 inch (0.76 m) centers for improved bridge shear transfer and side-wall buckling stability. The bulkheads are sandwich laminates composed of four plies of the above tri-axial fabric (laminate skin = 0.144 inch, 3.66 mm) SCRIMPed to a two inch (50 mm) balsa core. The lower hull is slotted so that the bulkheads can be fitted and bonded in-place using six inch (15 m) wide graphite plain-weave fabric strips acting as a shear tie. Graphite/epoxy (AS4-D, (0/90) 5- harness satin) side wall hat stiffeners (stringers or panel breakers) were designed to be secondarily bonded to the mid-height of the vertical and angled side-walls. The use of these 56 stiffeners would greatly increase the potential side-wall buckling load by forcing the side-wall to buckle into its second length wise mode as opposed to its first mode. In the toe region (entrance, exit) of each treadway, solid composite upper/lower termination blocks are also SCRIMPed into the superstructure (lower hull) to provide adequate strength from potential localized crushing. These tapered blocks (two small upper blocks, one large lower blocks), are machined maple wood wrapped in eight plies of (±45) stitched graphite (T650) fabric to increase their strength.

The roadway deck designed to transfer vehicle wheel loads into global structural loads and to protect the treadway from impact stone loads. All concepts were based upon using an approximately 3.5 inch (89 mm) thick cored deck, which is composed of upper and lower 0.25 inch (6.5 mm) face sheets and a three inch (76 mm) core. Core structure selection was a design challenge to find a low-cost and low-weight approach that

1. Has outstanding thru-thickness compression and shear stiffness to withstand the large dynamic tank loads,

2. Ability to provide some in-plane compression stiffness in order to increase the bridge axial and transverse bending stiffness, and,

3. Easy to manufacture and able to conform to the curved upper surface. Eight candidates, for the core, were considered, including:

1. A SCRIMP approach developed by HardCore Dupont, using plain-weave graphite fabric wrapped around horizontal foam tubes having a square (3 inch, 76 mm) cross-section,

2. A SCRIMP approach developed by HardCore Dupont, using plain-weave fabric and unidirectional graphite face sheets and a three inch balsa (15 lb/ft^3) core,

3. A precured corrugated SCRIMP graphite/epoxy core that is foam filled and then SCRIMPed to upper and lower face sheets (Hard-core Dupont),

4. A SCRIMP approach developed by HardCore Dupont using plain-weave graphite/epoxy wrapped around short vertical (3 inch, 76 mm) cubes tubes commonly called Braid-Core,

5. Graphite-epoxy face sheets with pultruded graphite/epoxy (or vinyl ester) box beam or I-beam cores developed by MMFG (Morrison Molded Fiber Glass Company, Bristol, VA),

6. Graphite-epoxy face sheets bonded to filament-wound graphite/epoxy box tubes developed by ACPT (Advanced Composite Products and Technology, Inc., Long Beach, CA),

7. An assembled graphite thermoplastic deck, developed by TPI (Thermoplastic Pultrusions, Inc., Bartlesville, OK) that is composed of multiple thermoplastic pultrusions components (face sheets and triangular shaped core) that are assembled through reheating the thermoplastic resin, and,

8. An assembled deck system called Snap-Sat developed by COI Composites-Optics, Inc., San Diego, CA) that is composed of low-cost graphite/epoxy tooling sheets accurately water-jet cut into interlocking components that assembled and secondarily bonded together.

All of the deck concepts were first reviewed for weight and cost metrics before performing a detailed finite element analysis. Options (6-8) resulted in the lowest areal weights of 0.039, 0.047, 0.034 lb/in^2, respectively, but were cost prohibitive. Option (5) offered the potential for low-cost, low-weight (0.040 lb/in^2), and manufacturing ease, but standard pultrusions could not provide adequate through-thickness stiffness. Developing special pultruded dies to pull off-angle fibers was beyond the program constraints. Option (4) did not have adequate shear transfer between the face sheets and the braid-core. Finite element analysis revealed that Options (1-3) were feasible, but (3) would require special corrugated tooling that was beyond the time/cost constraints of Phase I.

The design of option (1) involved wrapping five plies of plain weave graphite (Hexcel AW370) around light weight (3 lb/ft^3) closed-cell foam members having a (3 inch, 76 mm) square cross section. These tubes were laid next to each other and then ten additional plies were laid across the top and bottom to form the face sheets. Thus the resulting deck skins had 15 plies of graphite fabric (0.265 inch, 6.7 mm), whereas the vertical side walls had of ten plies of graphite fabric (0.176 inch, 4.5 mm). The expected areal weight for this design was (0.042 lb/in^2). The actual fabricated decks had poor structural performance because it was not possible to achieve good compaction in the vertical webs during the resin infusion. The fabricated vertical webs were characterized as loose wavy fibers in a resin rich laminate where the fiber volume fraction was near 23-30%, as opposed to the deck horizontal upper/lower laminates of 55-60%.

The Option (2) development involved having upper and lower graphite/epoxy laminate face sheets of 0.252 inch (6.4 mm) thick and a three inch (76 mm) thick end-grain balsa (15.5 lb/ft^3) core. The face sheet stacking sequences were calculated to be $[F_2/U/F/U/F/U/F_2]$ where (F) is a graphite plain weave fabric and (U) is a graphite unidirectional tape orientated with the bridge axial direction. The heavier end-grain balsa core is required to provide adequate shear strength. The areal weight on this design is the heaviest 0.053 lb/in^2 while the deck cost is the lowest (2-8x less than others).

As a comparison, the areal weights of the current Heavy Assault Bridge (HAB) aluminum deck is (0.059 lb/in^2) and of an optimized U.S. Army Aluminum deck is (0.050 lb/in^2). It is interesting to note that the metallic deck areal weights, and respectively, are much heavier than the best composite designs, but are near the weight of the composite balsa deck (Option 2). Thus an Option (1) composite deck would weigh 2782 lbs per bridge, whereas the best Aluminum deck would weigh 3312 lbs, leading to a weight savings of 530 lbs per bridge.

The treadways were fabricated with a balsa core assembly, due to Phase I time/cost constraints that eliminated the best design approach (Option 3) and the lack of availability of three inch (76 mm) high density aircraft-grade balsa core. This balsa core assembly involved combining a two inch (51 mm) balsa core layer with a one inch (25 mm) balsa core layer, where two plies of woven graphite fabric are inserted between the balsa layers. The use of the balsa core assembly has one advantage in that the shear strengths of the ne and two inch layers have much higher shear strength than a single three inch thick layer (i.e., end-grain balsa shear strength is highly thickness dependent).

The wear surface design concentrated on three different approaches. The first approach involved an integral composite design of added glass or graphite woven or felt plies that would serve as sacrificial layers that could be worn away before reaching the critical structural plies. The second approach involves using an attachable (replaceable) metallic or polymer wear surface. The third approach uses a spray-on polymer (easily repairable) surface. This problem could not be computationally analyzed due to the severe nature of the tank loads. Instead, 14 different potential materials were attached to Army roadway panels and placed in the M1-A1 Abrams tank test track at U.S. Army Aberdeen Test Center, Aberdeen, MD for actual tank testing. The integral design approach with sacrificial plies failed in the first 1200 freeze/thaw crossings, as a thermal mismatch delamination between the structure and sacrificial plies. The spray-on polyurethanes performed near flawlessly over 3200 crossings. The treadway design also includes Aluminum end-caps that are defined as a box beam (Al 6061-T6, 0.375 inch wall) with butt-welded upper/lower face sheets The launch rail design was not addressed during this first phase of this program. The overall bridge weight was calculated as: 9494 lbs (4302 kg) with the corrugated deck and 10,500 lbs (4760 kg) with the Phase I treadway with the balsa core deck.

Structural Analysis

A detailed linear static, nonlinear buckling and free vibration finite element analysis of a single treadway was performed using NASTRAN. The global model of the treadway was composed of 22,000 elements and had 28 different property sets. The 28 different material property sets are used for the different laminate definitions of the treadway including the local ply drop-offs of the unidirectional quilts and local build-up of the side-walls of the superstructure near the end-ramps.

Five different vehicle loads were considered (MLC-50 hypothetical, MLC-70 real and hypothetical, MLC-110 real and hypothetical), at three different positions on the bridge (entrance ramp, mid-span centered on bridge and mid-span with tank treads off centered). The real MLC-70 vehicle represents the worse load case. The following four boundary conditions were the most critical:

1. Simply supported level,

2. Simply supported uphill (1:10),

3. Simply supported twisting (1:20), and,

4. Distributed support (side wall buckling).

Under these worst case applied loadings, the bridge maximum center span deflection is 3.5 inch (89 mm). In addition to these static vehicle load cases, the loads were increased by the following factors: (1.2) impact factor (static approximation of dynamic loads), (1.26) eccentricity factor and (1.8) safety factor using B-basis material allowables.

Margins of Safety (MS) were calculated throughout the bridge for all load cases using two different approaches. The first approach involved using calculated laminate strains with experimentally measured coupon failure strain (preliminary B-basis allowable [9,10] and the maximum strain theory. The second approach involved using calculated lamina stresses with experimentally measured coupon strengths (preliminary B-basis allowable [9,10]) and the Tsai-Wu failure criteria. [11] The preliminary B-basis allowable strengths (or failure strains) are defined as the strength (or strain) value at which "90% of all coupon test results are expected to fall below this value with a confidence of 95%." The vales are experimentally determined from replicated ASTM specified tension, compression and shear test and a statistical approach assuming the measure test scatter is random. This approach is accepted by the aerospace industry for material qualification. See section on Material Testing for more details. The calculated safety margin is +0.5 in the upper roadway deck, +0.3 in the side walls and +4.5 in the lower most tension members.

In addition to the large global models, a series of small local models were constructed in order to size and locate the bulkheads, to design the "buckling resistant" side-wall stiffeners (3 inch (76 mm) deep stringers), and define the corrugation of the deck. From these it was determined that side wall hat stiffeners (stringers) and 30 inch (0.76 m) bulkhead spacings significantly increase the buckling load by forcing the side wall to buckle into its second mode shape.

Fabrication

The treadway is an assembly of prefabricated SCRIMPed components that are either secondarily bonded or SCRIMPed together. The fabrication procedure involves:

1. Manufacturing the individual components (17 balsa laminated bulkheads, 17 bulkhead caps, 56 trapezoidal stiffeners, upper/lower termination bulkheads, lower superstructure hull),

2. Assembling the lower superstructure, and,

3. Installation of the roadway deck.

Individual Components

The 17 internal sandwich type bulkheads are constructed of outer laminates compose of four plies of 34 oz tri-axial stitched carbon fabric [±45/90] laid up in an omnitriax orientation and a two inch (51 mm) thick 15 lb balsa core. All bulkheads (and other components) were SCRIMP infused using a Shell based epoxy resin (53% Shell EPON 862, 47% Lyndride 6K mixed in a dynamic mix chamber at oven temperature). The bulkheads were infused at 160°F (71°C), then post-cured at 200°F (93°C) for a period of two hours. The parts were demolded, custom trimmed and sand blasted for later bonding. The 56 trapezoidal stiffeners were fabricated out of four plies of 20 oz bi-directional [0/90] fabric that was laid-up on male steel tools, SCRIMPed using the same resin/cure and then trimmed and sandblasted. Next, 15 lb balsa is cut to fit into the trapezoidal pocket, where they are bonded in place using an epoxy (Ciba TDT-177-149-b). The assembly is then heated to 200°F (93°C) for two hours, to post cure the adhesive. The lower superstructure hull was fabricated in a single SCRIMP operation, but required a number of critical steps in order to insure its integrity. First, a large accurate steel tool was fabricated, including removable vertical side walls to aid in part removal. Next, two different fabrics were used in the lay-up: stitched uni-directional quilt and (34 oz) tri-axial stitched carbon fabric [±45/90]. This lay-up included:

1. Six plies of tri-axial fabric in the vertical and angled side walls that are increased to 10 plies as one gets near the end caps, and

2. The lower tension rails included the six tri-axial plies wrapped around from the side walls with an additional 40 plies of unidirectional stitched packs that are interwoven. These 40 plies are dropped to 16 plies near the end caps. The lower hull was SCRIMP infused in a 50 ft (15.24 m) oven using the same resin/cure/post-cure. The hull was demolded and the vertical side walls were trimmed to the desired circular arc.

Lower Superstructure Assembly

The lower superstructure is finished in a five step process. First, seventeen grooved slots are cut into the lower hull and the neighboring area is sand blasted. Second, the bulkheads are bonded into the lower hull using for- and six inch wide graphite fabric acting as a shear tie. The bonding resin is a Ciba TDT 177-151, which is an experimental low viscosity epoxy system for VARTM usage that cures at room temperature and has excellent properties. Third, fifty-six trapezoidal side wall stiffeners are bonded (Araldite AV 8531/ hardener HV 8531) at mid height to the vertical and angled side walls, Fourth, the lower and upper termination bulkheads are sandblasted and secondarily bonded into place. Fifth, bulkhead endcaps are secondarily bonded to the top of each bulkhead to transfer deck loads into the internal bulkheads (Figure 3).

Roadway Deck Installation

The roadway deck that attaches to the top of the lower superstructure assembly, was designed as a corrugated deck assembly that provided both compression stiffness and impact resistance in a light weigh assembly. But due to manufacturing cost and developmental time constraints, a two-layer balsa core assembly would replace the planned corrugation core during Phase I. In this section, the designed manufacturing procedure for the corrugated deck is presented, followed by the actual procedure for the as-built balsa core assembly.

The fabrication plan for the roadway deck with a corrugated core involved the following steps. First, a thin (0.060 inch, 1.5 mm) precured graphite/epoxy seal ply is bonded to the completed lower superstructure assembly, where all edges are bonded and sealed. This surface acts as the tool surface for SCRIMPing on the roadway deck. Second, the nine-ply lower deck laminate is laid onto the seal ply surface and has a six inch (152 mm) drape over the lower superstructure side wall to provide a suitable shear tie. Third, a three inch (76 mm) thick precured corrugation ribbon cor is laid on top of the lower deck laminate, then a lightweight (3 lb/ft^2) fill foam is pressed into the corrugation and hot wire cut smooth to surfaces. It's purpose is to insure that SCRIMP based epoxy resin doesn't fill the corrugation channels. Fourth, the nine-ply upper deck laminate is laid on top of the corrugation, where this laminate is cut to drape 10 inches (0.25 m) over the lower superstructure. This region is bagged, sealed and SCRIMPed to wet out and bond the roadway deck to the lower superstructure.

The substitution of the balsa deck core for the corrugation core required that the above third step be replaced with the following. After the lower laminate is laid onto the seal ply, a two- inch thick end grain balsa core is laid onto the laminate, next two plies of plain weave graphite fabric, followed by a one inch thick end grain balsa core. Lastly, the aforementioned upper laminate is laid up on top of the core with a ten inch drape onto the vertical side walls. The balsa core was slit on two inch centers to allow resin to thoroughly wet from the upper laminate to the lower laminate.

Treadway Finishing

The treadway is finished by secondarily bonding on prefabricated end cap assemblies (close-outs). The wear surface is attached to the upper roadway deck surface and the lower tension rail surface to protect from vehicle wear and stone impacts.

Table 1. Composite material test results.

	Graphite (5-Harness Satin)					E-Glass (Biaxial)
	Vinyl Ester (Rubber Tough)	Epoxy (Room Temp)	Epoxy (Room Temp)	Epoxy (Room Temp)	Epoxy (Elevated T)	Vinyl Ester
	AS4-D /Dow 8084	T300 /TDT 177-151	AS4-D /TDT 177-151	AS4-D /DER 332	AS4-C /Epon 862	CM 5005 /Dow 411-350
E_1 (GPa)	57.1	50.4	55.3	59.7	66.1	27.0
E_2 (GPa)	53.1	51.4	57.4	57.1	60.1	25.6
G_{12} (GPa)		3.38	3.17		5.23	4.21
ν_{12}	0.110	0.0636	0.1037		0.0485	0.071
X_t (MPa)	566	486	607	548	828	592
X_c (MPa)	193	344	348	395	649	323
Y_t (MPa)	424	565	590	557	810	503
Y_c (MPa)				334		316
S (MPa)		79.6	79.0		118	76.8
V_f (%)		52.70	53.96		56.23	54.24
Void (%)		1.28	1.66		0.40	0.84

Developmental Experimental Studies

Four sets of developmental experiments were performed including:

1. Material testing,

2. Wear surface material selection,

3. Roadway deck, and,

4. Three different sub-scale treadway designs.

Due to space limitations, the sub-scale treadway studies will not be presented.

Material Testing

A materials qualification screening study was performed to arrive at the best resin and fiber combination for "SCRIMPed" bridge components. The resins that were investigated included: Dow 411-350 (vinyl ester), Dow 8084 (rubber toughened vinyl ester), Dow DER 332 Resin/DCH 99 hardener (epoxy), Ciba TDT 177-151 (epoxy), and the Shell Epon 862 Epicure (epoxy). The different fiber types include: AS4D (Hexcel) Unidirectional (24 oz/yd2) and 5-Harness Satin (24 oz/yd2), T300 (Amoco) Unidirectional (24 oz/yd2) and 5-Harness Satin (24 oz/yd2), and A370 (Hexcel) 5-Harness Satin 10.94 oz/yd2). The (0°) and (90°) direction lamina stiffness (E_1, E_2, G_{12}, ν_{12}), strengths (X_t, C_c, Y_t, Y_c, S), failure tension strains ($\varepsilon_{11}{}^T$, $\varepsilon_{22}{}^T$, γ_{12}), and compression strains ($\varepsilon_{11}{}^c$, $\varepsilon_{22}{}^c$) were determined by standard tension (ASTM-D 3039-76), compression (ASTM-D 3410-87), and in-plane (Iosipescu) shear (ASTM-D 5379-93) tests for polymeric composites. Some of the average laminate stiffness and ultimate strength properties are given in Table 1, where it is observed that graphite/vinyl ester resin (Dow 8084) provides unacceptably low compression/shear strengths as a result of improper fiber sizing. The room temperature epoxies (Ciba TDT 177-151, Dow DER 332 Resin/DCH 99) provided significantly better compression strength than the vinyl ester, but their "pot-life" was not long enough to fully we-out the entire treadway. The 1501°F (65°C) cure epoxy (Shell Epon 862 Epicure) provided the best tension, compression and shear properties and were only slightly lower than aerospace quality autoclave cured laminates. As a comparison, the final column is of a five harness satin laminate composed of E-glass/vinyl ester. It is interesting to observe that while the stiffness properties of the glass/vinyl ester laminate are lower than the graphite/vinyl ester laminates, the strengths of the "properly-sized" glass/vinyl ester laminate is higher in both tension and compression. Once the Shell Epon 862 Epicure Epoxy as selected as the best resin, then an experimental material characterization program was performed to generate allowable material stiffness, strength and ultimate strain values. This program involved testing two different laminate configurations (unidirectional fibers, 5-harness stain plane weave) at room temperature with moderate humidity. Each of the above three different test were performed in the (0°) and (90°) directions and replicated six times so that the preliminary B-basis allowable value [9,10] was calculated using,

$$B = X_{\text{average}} - 3.007\,(X_{\text{standard deviation}}) \quad [1]$$

Where, (B) is the allowable material property, and (X_{average}) and ($X_{\text{standard deviation}}$) are the average and standard deviation of the six measured test results, respectively. The strengths and strains for the fiber dominated laminates were based upon ultimate values. The strength and strains for the matrix dominated laminates were determined using 0.2% offset. The preliminary B-basis allowables for the two different laminates are given in Table 2.

Table 2. Preliminary B-basis laminate material properties.

Type:		5 Harness Satin Fabric	Unidirectional Fiber
Fiber:		Grafil TR 30S 12K	Akzo Fortafil 50K
Resin:		Epon 862	Epon 862
Layup:		$[0]_4$	$[90]_4$
V_F	(%)	54-60	54-56
E_{11}^T	(GPa)	52.0	81.7
E_{11}^C	(GPa)	45.1	73.4
E_{22}^T	(GPa)	42.0	4.34
E_{22}^C	(GPa)	50.4	7.03
G_{12}	(GPa)	2.76	2.48
ν_{12}	-	0.044	0.325
X_T	(MPa)	607	882
X_C	(MPa)	381	530
Y_T	(MPa)	580	16.6
Y_C	(MPa)	377	79.2
S	(MPa)	38.4	32.6
ε_{11}^T	(μm/m)	8120	8440
ε_{11}^C	(μm/m)	6360	6120
ε_{22}^T	(μm/m)	8290	1210
ε_{22}^C	(μm/m)	6450	10650
γ_{12}	(μm/m)	5600	6520

A series of SCRIMP "adhesion" studies were also performed to assess the quality of the bond between embedded metallic (or precured composite) subcomponents and the SCRIMPed epoxy resin. Five different surface preparations were investigated including: as finished, bead-blasted, hand sanded, acid-wipe and sanding/acid-wipe. Hand sanding with the acid wipe produced the best shear bond of nearly 3000 lb/in^2 (20.7 MPa), whereas the other procedures produces shear bond on the order of 1500-2000 lb/in^2 (10.3-13.8 MPa).

Wear Surface Testing

The wear surface design concentrated on three different approaches:

1. An integral composite design of added glass or graphite woven or felt plies that would serve as sacrificial layers that could be worn away before reaching the critical structural plies,

2. Using an attachable (replaceable) metallic or polymer wear surface, and

3. Using a spray-on polymer (easily repairable) surface.

The attachable metallics provide well understood behavior and low cost, but with the concerns of corrosion and thermal mismatch. Attachable non-metallics offer a low cost solution, but have concerns that include UV stability, abrasion and puncture resistance, high temperature problems, limited life, and flammability. These materials include thermoplastic resins (AZDEL) which offer structural stiffness and strength, urethane sheets/coatings which have excellent wear resistance but offer no structural advantage and rubber sheets (Santoprene) which provide toughness and wear resistance, but also are heavy.

Fourteen different potential materials of thickness 0.25-0.28 inch (64-71 mm) were attached to Army roadway panels and places in the M1-A1 test track at the U.S. Army Aberdeen Test Center, Aberdeen, MD for actual tank testing.

Table 3. Candidate wear surface materials.

Biaxial [0/90] E-Glass/Vinyl Ester	Biaxial [0/90] E-Glass/Vinyl Ester (felt skin)
Quad[0/±45] E-Glass /Vinyl Ester	Quad[0/±45] E-Glass /Vinyl Ester (felt skin)
Biaxial [0/90] Graphite/Epoxy	Biaxial [0/90] Graphite/Epoxy (felt skin)
Quad[0/±45] Graphite/Epoxy	Quad[0/±45] Graphite/Epoxy (felt skin)
Attached Urethane Sheet	Spray-On Polyurethane
Rubber (Santoprene)	AZDEL (Thermoplastic/glass)
Titanium (Ti-6Al-4V)	Aluminum (7072-T6-T651)

See Table 3 for material definition. The first four on the right and left side of the table represent potential integral deck materials, where the right side has an added felt layer to act as a sacrificial ply. These materials include graphite (AW-370 11 oz 5-Harness Satin), E-glass (CM-5005 biaxial and QM6408 quad), vinyl ester DOW 8084), and epoxy (Ciba TDT-177-151). The next four represent potential nonmetallic wear surfaces. The final two represent attachable metallics (Aluminum, titanium) which also serve as experimental controls.

The two-part test involved:

1. 1200 speed controlled (10 mph maximum) tank crossings during the winter months to experience the freeze/thaw conditions, and,

2. 2000 high-speed tank crossings during the hot wet summer.

During the first part, the roadway panels were located just before and after a military bridge that was undergoing speed-limited, 10 mph (16 km/hr) fatigue testing. During the second part, the panels were placed on the track location that experienced 20-40 mph (30-65 km/hr) tank speeds. After 1200 speed controlled winter (freeze/thaw) crossings, only one material failed; Rubber Santoprene. Two other materials; Quad glass and Quad graphite with the sacrificial felt skin were showing signs of delamination into the felt skin. After the additional 2000 high speed crossings, no other material failed, but the composite laminates (glass/vinyl ester, graphite/epoxy) showed signs of wear (sacrificial plies worn away with damage into the structural fibers). Of all the potential wear materials, the "Spray-On" Urethane had no visible signs of wear.

Roadway Deck Testing

Early in the program, "low-cost" composite decks were fabricated for structural testing. Theses decks involved wrapping five plies of plain weave graphite (Hexcel AW370) around light weight (3 lb/ft^3) closed-cell foam members having a (3 inch, 76 mm) square cross section. These tubes were laid next to each other and then ten additional plies were laid across the top and bottom to form the face sheets. Thus the resulting deck skins had 15 plies of graphite fabric (0.265 inch, 6.7mm), whereas the vertical side walls had ten plies of graphite fabric (0.176 inch, 4.5 mm). The decks were SCRIMPed at HardCore Dupont using a room temperature cure vinyl ester (DOW 8084) resin.

These decks were statically tested at UCSD along with two existing metallic Arm bridge decks, which served as benchmarks. The first metallic bridge deck, which is used on the U.S. Army's Wolverine Heavy Assault Bridge (HAB), is fabricated from an aluminum extrusion. It is geometrically characterized as having an overall depth of 2.9 inch (74 mm) and upper and lower face sheets of 0.200 inch (0.51 cm) thick and

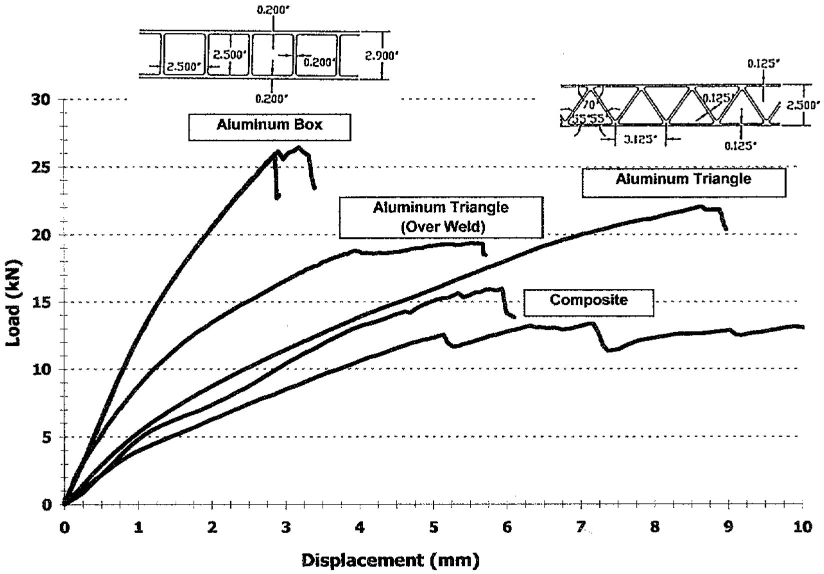

Figure 4. Experimental behavior of a composite (SCRIMP vinyl ester) deck, an aluminum box like deck (U.S. Army Wolverine HAB) and an aluminum triangular deck (U.S. Army design) subjected to a simulated rock-type load.

vertical webs of 0.200 inch (0.51 cm) thick separated by 2.5 inch (63.5 mm). Its cross section is presented in Figure 4 as the aluminum box design. The second metallic deck, which was developed by the U.S. Army for assault bridging applications, is also fabricated by welding together Aluminum (Al 7000) extrusions. It has an overall depth of 2.5 inch (63.5) and upper and lower face sheets of 0.125 inch (3.18 mm) thick. It has a triangular web core, where all webs are 0.125 inch (3.18 mm) thick and the webs have an included angle of 70 degrees and two complementary angles of 55 degrees. This design is called the Aluminum triangle and is also presented in Figure 4.

Experimental tests were performed to investigate four different deck failure modes, including;

1. Surface damage from stone (point wise) crushing contact,

2. Web core buckling from tank axle (line) loads,

3. Web core (or face sheet) shear failure from tank axle loads adjacent to the web core, and,

4. Face sheet bending failures from the tank axle places midway between the webs.

Stone type crushing of the upper deck surface stone was studied by loading with a one inch (2.54 cm) diameter impactor having a spherical tip of 0.5 inch (1.27 cm) radius. The load deflection curves for the three different deck designs are presented in Figure 4, where each design was tested. The two tests of the Aluminum box design were nearly identical, the composite designs had very similar loads, and the aluminum triangle design was tested over and away form a seam weld. Although the composite decks didn't perform as well as the metallic decks, they did support sufficient load, so that combined with an adequate wear surface, they will be at least equivalent to metallic decks.

The second study involved applying a narrow line load that simulated a tank axle, directly over the web on the three different designs. The narrow line load (0.5 inch, 1.27 cm wide) ran the length of the deck specimen. The metallic decks are able to withstand 11,750 and 15,000 lbs/in (2.06 and 2.63 kN/mm) whereas the composite decks are able to withstand 6,750 to 7,750 lbs (1.18-1.36 kN/mm). The low buckling load in the composite decks is associated with loose wavy fibers in poorly compacted vertical webs. Attempting to straighten the webs fibers by pressing the wrapped foam tubes together (improve compaction) during the SCRIMP operation, had no effect on improving the buckling loads. This occurred because even the slightest waves in the vertical web fibers will drop the buckling load. Thus, the only way to improve the web buckling loads is to either significantly increase the web thickness or insure that the fibers are absolutely straight by using precured laminates or pultrusions. Although the composite loads are approximately half of the metallic loads, there is still plenty of margin (nearly seven times) over the trilateral code requirements (0.175 kN/mm). [3]

The third study involved placing the line load (simulated tank axle) adjacent to the deck web to induce the maximum shear into the web/deck interface, where failure is characterized by deck shearing next to a web (Figure 5). The metallic decks failed at 3,430 lb/in (0.6 knN/mm) and 8,000 lb/in (1.4 kN/mm) which is much lower than the web buckling studies. The composites decks failed at slightly lower load of 4850 lb/in (0.85 kN/mm), where failure was characterized by through thickness shear cracking of the deck skins. The composite decks performed as good or better than existing metallic decks and nearly five times better than the code requirements (0.175 kN/mm). [3]

The fourth experimental study placed the line load midway between adjacent webs to induce the maximum stress in the deck skins and webs. See Figure 6. The Aluminum box deck failed at 3310 lb/in (0.58 kN/mm) and the Aluminum triangular deck failed at 1370 lb/in (0.24 kN/mm). The composite decks failed at 1310 lb/in (0.23 kN/mm), which is nearly comparable with the Aluminum triangular design, but is still 30% better than the code requirements of (0.175kN/mm). [3]

Full-Scale Composite Treadway Testing

As part of the Phase I program, a complete CAB treadway was structurally tested at the Charles Lee Powell Structural Systems Laboratories, on the

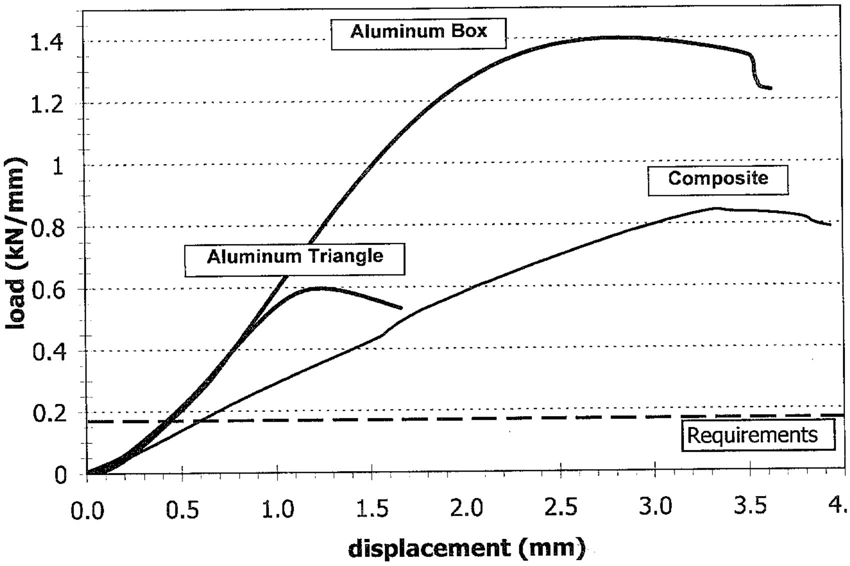

Figure 5. Experimental behavior of a composite (SCRIMP vinyl ester) deck, an aluminum box like deck (U.S. Army Wolverine HAB) and an aluminum triangular deck (U.S. Army design) subjected to a line load adjacent to the web (maximum shear case).

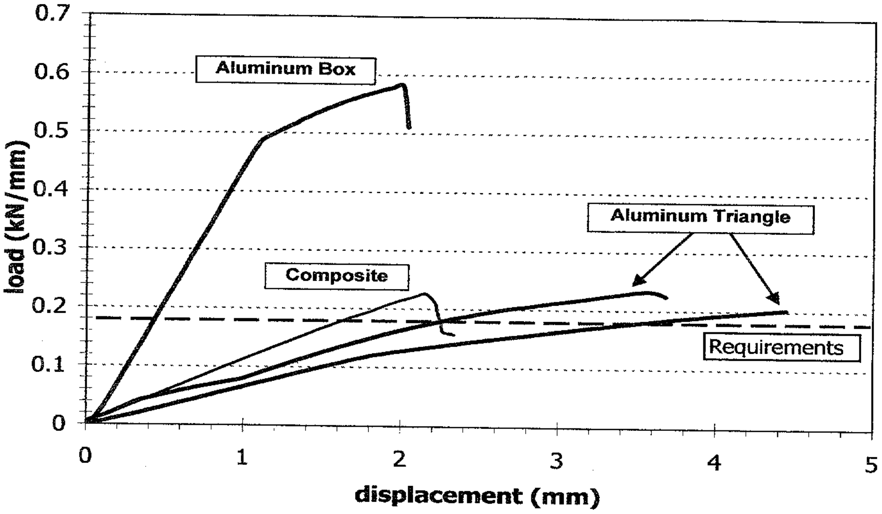

Figure 6. Experimental behavior of a composite (SCRIMP vinyl ester) deck, an aluminum box like deck (U.S. Army Wolverine HAB) and an aluminum triangular deck (U.S. Army design) subjected to a line-load midway between webs (maximum bending case).

campus of the University of California Sand Diego. The test involved first structurally characterizing the stiffness of a treadway for the purpose of correlating with the finite element models and check manufacturing consistency, and then performing a strength test to determine the failure load and failure location.

Test Set-Up

The basic test set-up involves placing the CAB treadway on hardwood end supports in a horizontal positions with no rake or side-slope, where the loading simulates an M1-A1 tank load distribution centered on the treadway mid-span. The treadway boundary definition involved using hardwood (apitong) blocks and 1.5 inch thick elastomeric bridge pads. See Figure 7. These mounting supports were developed at UCSD and approved by U.S. Army TACOM. The mounting block structures are 25 inches along the treadway length, 72 inches long (12 inches wider than the 60 inch treadway), and 16 inches high (four 4 inch thick bonded blocks). The blocks are placed on top of a hydrostone bed on the test floor to ensure that the upper surfaces of the mount blocks are horizontal and level with no twisting. The inner distance between the two mounting blocks is 481 inches and the outer distance is 531 inches. Thus, the test simulates crossing a 40.1

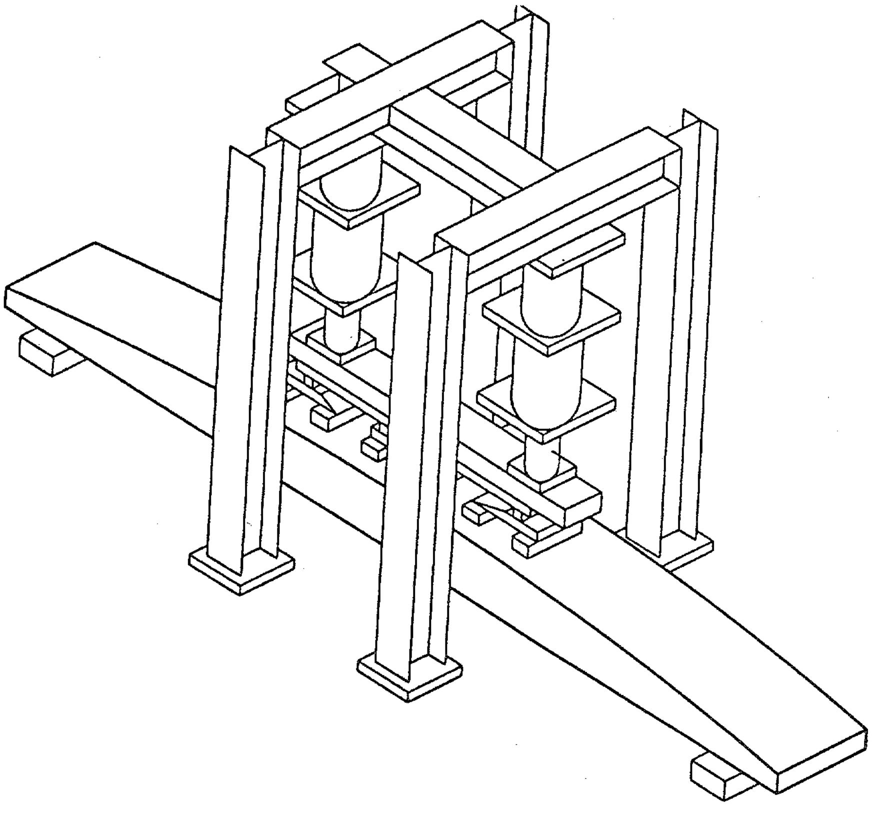

Figure 7. Sketch of static treadway showing treadway, boundary mounting supports, load frame, two MTS 220,000 lb (980 kN) actuators and U.S. Army whiffle tree.

foot (12.2 meter) gap. The CAB treadway is centered between the mounting supports.

The loading was applied using a large test frame including two MTS 220 kip (220,000 lb, 980 kN) actuators and a U.S. Army supplied whiffle tree assembly. The whiffle tree assembly, which was developed by the U.S. Army Belvoir RD&E Center, applies the near-exact moment distribution "foot-print" of a combat-loaded M1-A1 tank. Thus, applying total actuator loads of 70,000 lbs (311 kN) will simulate the loads that a 70-ton M1-A1 tank would apply to a single CAB treadway. The whiffle tree was centered along the CAB treadwayspan as well as across the width. Thus, simulating an M1-A1 tank parked on the CAB mid-span. The maximum load that was planned for the CAB treadway was a 116,000 lb. This "proof" load is composed of the following components:

70,000 lb	(310kN)	(1/2 "nominal" combat-ready M1A1 tank loading)
x 1.26		(Side Load/Eccentricity Factor (63%/37%) split)
x 1.20		(Impact Load Factor)
x 1.10		(Design overload proof load factor)
116,000 lbs	(516kN)	**(MAXIMUM TEST PROOF LOAD)**

The treadway was instrumented using 23 LVDT's and 52 externally mounted strain gage rosettes to monitor their behavior under load. See Figure 8 for location for strain gauge placement. The external strain gage rosettes were strategically placed to monitor strain levels in the lower tension rails, the upper deck, the side walls (potential buckling), and at the terminations sections were the highest strain levels were expected. In addition, load and displacement measurements for each of the two actuators was also monitored. Of the 23 LVDT's, eight were used to monitor the mount block displacements and treadway end rotations and five were used at stations (120, 270, 420) to monitor the vertical displacements of the deck and lower tension rails and the horizontal displacement at the mid side wall height. The loading was applied at a rate of 1000 lb/minute (4.45 kN/minute) and all measurements were sampled at 100 lb (445 N) load increments.

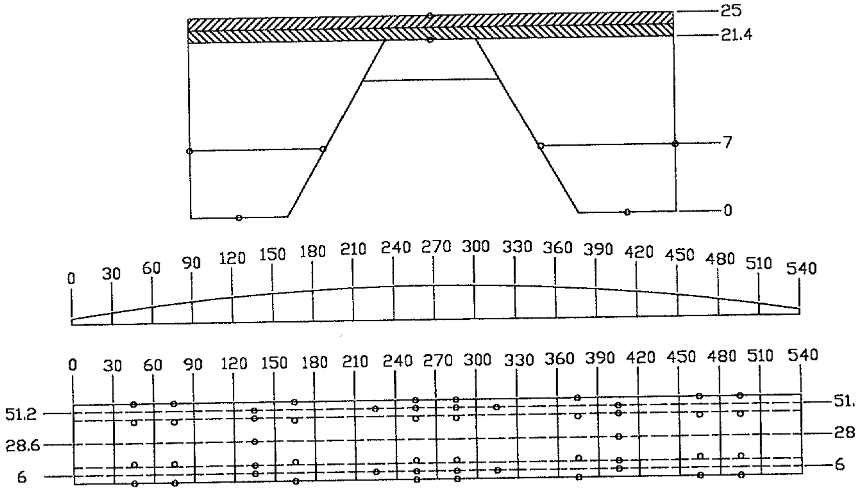

Figure 8. Placement of 52 strain gage rosettes on external structure.

Treadway Test

The loads were applied in the following cycles:

Cycle 1: (0-10,000 lbs (44.5 kN) - 0)
Cycle 2: (0-20,000 lbs (89.0 kN) - 0)
Cycle 3: (0-30,000 lbs (133 kN) - 0)
Cycle 4: (0-40,000 lbs (178 kN) - 0)
Cycle 5: (0-60,000 lbs (267 kN) - 0)
Cycle 6: (0-75,150 lbs (334 kN) - 0)*
Cycle 7: (0-15,000 lbs (66.8 kN) - 0)

***Failure**

The mid span (station 270) vertical displacement is presented in Figure 9. During the fires five cycles there was slight minor matrix cracking, but the loading response was linear with a measured flexibility of 0.028 in/Kip (0.16 mm/kN), which was corrected of support flexibilities. During the sixth cycle, there was a loud crack at 75,150 lbs (334 kN)

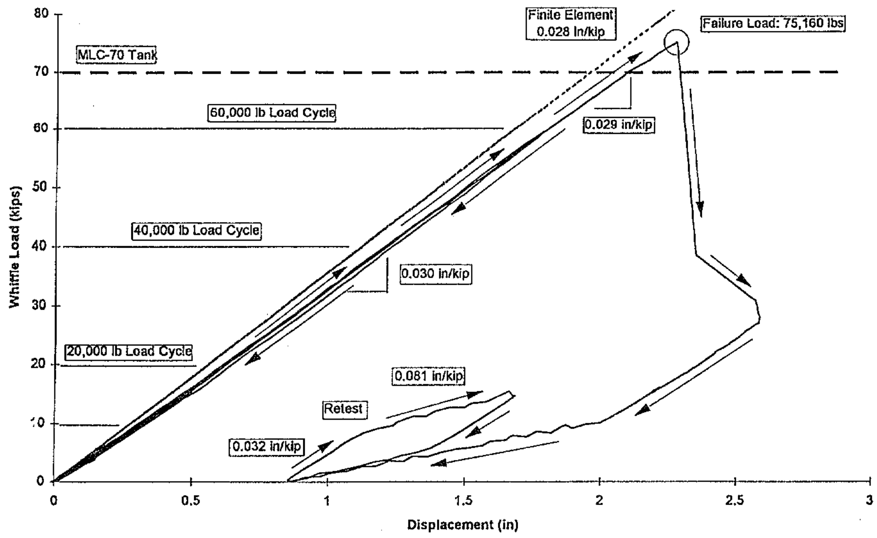

Figure 9. Mid-span vertical displacement of the underside of the upper deck (station 270).

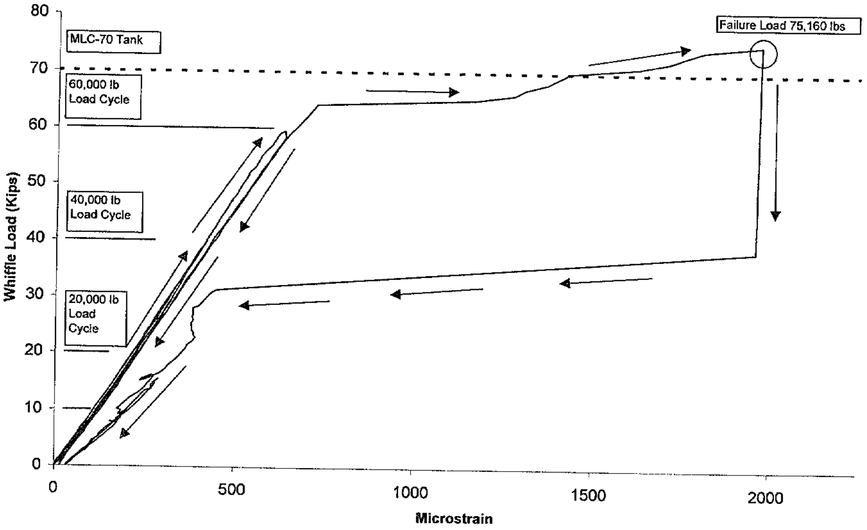

Figure 10. Outer vertical side wall shear strain (station 45).

coming from the internal deck between stations 50-150. The structure could no longer maintain load as the displacement increased. Initial external (visual, coin tap) inspections did not reveal noticeable local damage except for a permanent set of the bridge of approximately 1.00 inch (2.54 cm). A seventh cycle was attempted to check the change in structural stiffness of the treadway. During this loading it was clear that the treadway was starting to twist (0.011 degree/Kip, 0.00247 degree/kN) and the treadway flexibility was much higher (0.032 in/Kip, 0.183 mm kN).

In general, the seventeen vertical LVDT's responded linearly with no hystersis, up to the failure load, whereas the six horizontal LVDT's that were mounted to monitor sidewall buckling showed no displacement. An examination of the 52 externally mounted strain gage rosettes revealed that 44 of the rosettes were perfectly linear with no hystersis up to the ultimate failure load, but that eight rosettes mounted on the sidewalls near the treadway ends showed some varying stages of nonlinearity (permanent deformation) above 65,000 lb (289 kN) of applied load, (Figure 10). Further examination of the vertical and angled wall strains revealed that an internal structural failure near 65,000 lbs (289 kN) changed the load path away from the angled walls to the vertical loads. The most likely scenario for this is if the upper deck isn't fully attached to the lower hull just above the inner angled walls, but remains attached to the hull along the outer vertical walls. This drives the shear away from the inner angled walls towards the outer vertical walls, thus overloading and failing the vertical wall bonds Post-test sectioning of this region verified dry fabric in the lower deck region above the angled walls which was attributed to a poor wet-out condition during the SCRIMP fabrication of the deck to the lower hull. Further sectioning and microscopic inspection revealed that the lower tension rails, the side-walls and the bulkheads were fully wet-out over the entire treadway length. Moreover, the interlacing of the side-wall fabric to the lower uniaxial plies was good. Thus the SCRIMP process is a viable manufacturing process for the CAB treadway since the critically thick regions (1.25 inch (32 mm) thick lower tension rails) performed flawlessly, but further investigation is needed to simplify the manufacturing process in the highly stressed regions.

Conclusions

In this paper, the Phase I progress of the DARPA-sponsored CAB development program was reviewed including; Army requirements, bridge design, analysis, low cost fabrication techniques using the SCRIMP process, developmental experimental testing and static testing of a full scale treadway. A detailed weight and cost analysis of the current composite bridge reveals that it will weigh 25% less and cost 20% less than an existing metallic (Aluminum) bridge. An examination of the experimental results reveals that the SCRIMP process appears to be a viable manufacturing process for the CAB bridge since the critically thick regions performed flawlessly, but that further work is needed to simplify the manufacturing process in the mostly highly stressed regions. During Phase II of the DARPA program, the treadway design will be refined to further lower cost and weight by removing excess material in high safety margin areas.

Acknowledgments

The authors gratefully acknowledge the support of this research from the DARPA TRP contract MDA972-94-3-0030 and the technical guidance by the monitors: Steve Wax and Jon DeVault. In addition, the authors wish to acknowledge the efforts of Hexcel Corp. and Amoco for supplying the graphite materials and Trans-Science Corp. for many of the engineering drawings. Lastly, the authors wish to thank Geoff Appuhn, David Dillon, Cindy George, Wilder Grippo, Citra Ie, Kevin Napalitano, John Suchy and David Wolfe, of the Division of Structural Engineering at UCSD for performing the finite element analyses and the experimental tests and Chris Thompson and Mike Grunza of HardCore-Dupont for analyzing and fabricating the hardware.

References

1. Bustin, I., "Military Bridging Programs for Armored Vehicles," *Military Technology*, Vol. XVII, Issue 2, pp. 50-61, February, 1993.

2. Bischmann, P., "River Crossing in the Central Region," *NATO's Sixteen Nations*, Vol. 3, pp. 76, 1985.

3. "Trilateral Design and Test Code for Military Bridging and Gap-Crossing Equipment," Trilateral Design and Analysis Group of the United States, Federal Republic of Germany and the United Kingdom of Great Britain, January, 1996.

4. Maass, D. and Makwinski, M., "Development of a Lightweight Durable Thermoplastic Roadway Surface for Military Bridge Site Access/Egress," *Advanced Composite Products*, ACP-TR-70, December, 1992.

5. Bullock, D. Boyce, J. and Kashalikar, U., "Composite Bridge Deck," Foster-Miller, Inc. Final Report, MER-0036-FM-8624-412, January, 1991.

6. "Military Standard Transportability Criteria," Department of Defense, MIL-STD-1366C, February, 1992.

7. "Military Standard Slinging and Tiedown Provision for Lifting and Tying Down Military Equipment," Department of Defense, MIL-STD-209H, June, 1991.

8. "Research, Development, Test and Evaluation of Material for Extreme Climatic Conditions," Headquarters Department of the Army, AR 70-38, September, 1979.

9. "Department of Defense Handbook, *Polymer Matrix Composites*, Volume 1. Guidelines for Characterization of Structural Materials," Department of Defense, MIL-HDBK-17-1E, January, 1997.

10. "Department of Defense Handbook, *Polymer Matrix Composites*, Volume 3. Material Usage, Design and Analysis," Department of Defense, MIL-HDBK-17-3E, January, 1997.

11. Tsai, S.W. and Wu, E.M., "A General Theory of Strength for Anisotropic Materials," *Journal of Composite Materials*, Vol. 5, pp. 58-80, 1971.