# Design and Analysis of Thermoplastic Composite Bridge Superstructures

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**16. Abstract**

This study is primarily focused on addressing the application of fiber reinforced composites (thermoplastics) in the design of bridge decks. Bridges are vital components of the nation's infrastructure, many of which are deteriorated. The replacement of such bridges requires careful planning as well as exploration of other materials that will resist the factors leading to the deterioration of old bridges, which in many cases need to be replaced before reaching 50 percent of their expected service life.

In this study we present an integral modular fiber thermoplastic composite bridge structural system. The design concept is presented by utilizing high performance thermoplastic material (i.e. Glass/Polypropylene) along with an efficient low cost manufacturing process and fabrication technique. The design is based on detailed finite element analyses and limited experiments to investigate the stiffness and strength of the structural system. To demonstrate the design concept, two bridge deck systems with different spans were modeled and compared with two current thermoset composite bridge systems. The proposed design concepts for both decks present a unique approach for structurally efficient and low cost bridge deck systems.

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# Executive Summary

Thermoplastic composites are relatively new material in civil engineering applications and lack a history of use in civil infrastructure. Due to the number of unique advantages of thermoplastics over traditional materials, i.e. steel, concrete and thermosetting composites, their use in civil infrastructure (bridge decks in this study) can yield structurally efficient and cost-effective structures. This research work focused on the application of thermoplastics (E-glass/Polypropylene (PP)) in the design of bridge decks.

High quality, low cost thermoplastic composites can be produced by using a hot melt impregnation technology (DRIFT- Direct ReInforcement Fabrication Technology) that allows complete impregnation of continuous fibers with thermoplastic polymers. The products manufactured by this process in the form of continuous rods and tapes can be further processed using injection or compression molding.

In this study the deck shape presented was based on the hat-sine rib stiffened design concept; the shape was selected by considering manufacturing issues such as the processablilty of the thermoplastic E-Glass/PP woven tape and practical issues such as tooling and design flexibility for the prototype studies. The loading conditions and performance limitations described in the AASHTO LRFD Bridge Design Specifications were adopted for this study and the finite element analysis to model the bridge deck was carried out on Ansys 8.0 software.

The performance of the conceptual deck design was demonstrated by studying typical single lane and two lane bridge decks. The design of both decks was based on a flat panel bonded to a flattened sine wave rib structure controlled by AASHTO deflection standard under the maximum vehicular loading condition. In both deck systems (single lane and double lane) the outer shell (top flat face) with sine ribs provided an efficient and economical section.

The deck analysis methodology, based on finite element modeling, predicted performance results consistent with those obtained experimentally for the modular type fiber composite deck system. The finite element model showed a variation of 10% to 15% from observed results, which could be reduced by more closely defining the experimental conditions.

The proposed design concept was compared with a Lockheed-Martin bridge design which was described by Dumlao et al. (1996), and with a published thermoset composite bridge deck concept proposed by Aref (2000). Our proposed design yielded higher deck self weight and consumed more materials, but it could result in a superior low cost deck section based on the manufacturing and material cost comparison. E-Glass/PP is much less expensive than S-glass and the manufacturing process associated with it yields very good cost effective results under higher production rates. E-Glass/PP also has potential uses in damage and impact scenarios in bridge structures.

# Section 1
# Introduction

## 1.1 Background

The United States of America is facing a major challenge to keep the nation's infrastructure systems in usable condition. Among the infrastructure systems, a large portion of highway bridges are classified as "deficient". Nearly 28 percent of the 590,000 public bridges were rated either structurally deficient or functionally obsolete as of the year 1997 (USDOT, 2000). The situation is expected to worsen because a large number of bridges were built in the 1960's (the Interstate era) and they will need more maintenance, major rehabilitation, or replacement in the near future. According to the same study, bridge decks are ranked the number one bridge maintenance element at state departments of transportation. The United States Department of Transportation estimated the average annual cost just to maintain bridge conditions for the 20 year period from 1998 to 2017 will be \$5.8 billion and the average annual cost to improve bridge conditions would be \$10.6 billion in 1997 (USDOT, 2000). In 1997, federal, state, and local bridge expenditures totaled \$6.1 billion. These figures show that the annual investment in bridges will have to increase by at least \$4.5 billion from \$6.1 billion to \$10.6 billion for the 20 year period (1998 to 2017) in order to meet all current and future repair needs (USDOT, 2000). Thus it is imperative to build bridge systems that have long term durability and require less maintenance. A solution to this challenge may be to use new materials or to implement new structural systems.

About 70 years ago, fiber reinforced polymeric (FRP) composites were first introduced into the industrial world. Since then, FRP composite materials have been increasingly used in a variety of industries including aerospace, transportation, sporting goods, chemical engineering. More recently, FRP composites have been gaining market share in civil infrastructure applications due to their unique advantages over traditional steel and concrete materials. Despite the fact that FRP composites are very attractive materials to structural engineers due to their high specific stiffness, specific strength, and corrosion resistance, their application in civil structures still lags behind other industries primarily due to their high cost of manufacture and construction.

The current United States market for thermoplastic materials is in excess of $4.54 \times 10^8$ kg per annum (Husman et al., 2001). Thermoplastic composites typically comprise a commodity matrix such as polypropylene (PP), polyethylene (PE) or polyamide (PA) reinforced with glass, carbon or aramid fibers. Progress in low cost thermoplastic materials and fabrication technologies offer new solutions for very lightweight, low cost composite structures with enhanced damage resistance and sustainable designs (Husman et al., 2001). At present, there are no initiatives to use thermoplastic composites for bridge structures because of the perception of high cost and expensive manufacturing. The use of thermoset composites in bridge construction and repair, on the other hand, is relatively well established as previous work in composite bridges has focused on the use of thermoset composites to enhance strength and stiffness.

## 1.2 Research Objectives

The objectives of this research are:

1. To introduce the application of thermoplastics (woven glass/carbon fiber reinforced polypropylene) in the design of modular fiber reinforced bridge components.
2. To describe the behavior of the bridge deck design using the finite element method, which includes verification of stiffness, strength and other design features.
3. To compare and verify the experimental and finite element analytical results.
4. To compare the proposed deck design with other composite bridge deck designs.

## 1.3 Literature Review and Manufacturing Process of Thermoplastic Composite

Most of the thermoplastic composite materials used today are short fiber, compounded products consisting of glass fibers (typically 10 to 40 % fiber content by weight) in a low cost polymer matrix, e.g. polypropylene, polyethylene, nylon, polyester etc. (Husman et al., 2001). These compounded products are typically produced by blending chopped glass fibers and polymers in a high shear extruder, and extruding a composite rod that is chopped into pellets for injection molding processing. This process grinds the glass fibers to very short lengths (typically < 2mm). Although these composites have improved properties over un-reinforced matrix polymers, the full advantage of the reinforcing fiber is not achieved. Depending on the polymer used, these compounded products typically sell for $0.85-1.5 per pound (Husman et al., 2001).

Several long fiber (10 to 25 mm) compounded pellet products and glass thermoplastic composite sheet products provide better translation of fiber properties and better composite performance. The long fiber pellets have higher mechanical properties, higher notched impact strength, reduced creep tendency, and very good stability at elevated temperatures in humid conditions when compared with short fiber thermoplastics (www.ticona.com).

The process used to make long fiber thermoplastic products is generally more expensive than standard compounding, resulting in products typically selling from $1.20 to more than $3.00 per pound (Husman et al., 2001). Thus the market for long fiber thermoplastic composites has been very limited due to the high cost of producing these products. The market for thermoplastic composite products using fibers other than glass, such as carbon, aramids, or other fibers has also been very limited due to high costs.

Recently, a novel hot melt impregnation technology has been developed which allows complete impregnation of continuous fibers with thermoplastic polymers at very high production rates, producing high quality, low cost thermoplastic composites. This technology called DRIFT (Direct ReInforcement Fabrication Technology) produces products that can be made as continuous rods, tapes, and pultruded shapes, or that can be chopped into pellets of any length for injection or compression molding (Husman et al., 2001). The process has been shown to work well with glass, carbon, aramid, and other polymer fibers and also with a wide variety of thermoplastic polymers. The superior penetration and wetting of the yarns results in excellent mechanical properties and easier downstream processing for fabricated components. These materials can be fabricated into continuous and long fiber composite structures using low cost fabrication techniques such as extrusion/compression molding, injection, injection-compression, and vacuum thermoforming (Vaidya et al., 2003). Thus the ability to produce a wide variety of high performance, thermoplastic composite products at very low costs could be achieved.

The DRIFT process is a simple, robust hot melt impregnation technique that allows complete impregnation and wetting of continuous fibers at very high operating speeds. The process is shown schematically in Figure 1-1.

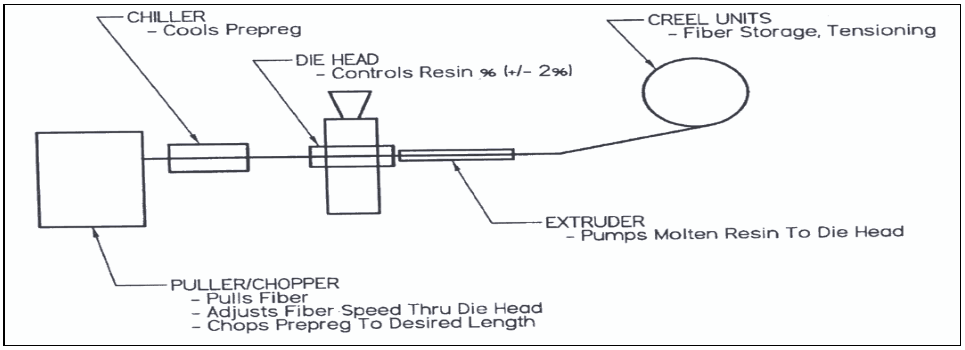

**Figure 1-1: Drift process (Husman et al., 2001)**

The components of the impregnation line consist of a fiber creel with tension control, a fiber heating oven, an impregnation die which is fed polymer by a standard extrusion machine, a chiller to cool the prepreg, and a puller that controls the line speed. The impregnated product can be taken up as a continuous tape/ribbon, which is the form it takes as it exits the impregnation die, or it can be collapsed into a continuous rod. Other product cross-sections can be created by forming the product as it is cooled. A chopper can also be inserted into the line to produce flakes or pellets of desired lengths, typically 0.25 to 1 inch or longer. The limits of the process for fiber content and control have not yet been established. The ultimate result of this process is the ability to produce very high quality composite products with a wide variety of fibers and polymers in a variety of product forms, at costs similar to the lowest cost compounding processes (Husman et al., 2001).

The DRIFT process could be used to produce E-glass/PP woven tapes, as it provides large volume production and excellent impregnation between fibers and the thermoplastic matrix with accurate control over matrix content. E-glass/PP tapes of 12 mm width and an average layer thickness of 0.6 mm have been produced using the DRIFT process. The unidirectional E-glass/PP tape material with a fiber content of 67% by weight (42% by volume) has a tensile strength of 87.6 ksi, tensile modulus of 4300 ksi, and a density of 99 pounds per cubic ft (Vaidya et al., 2004). The hot melt impregnated E-Glass/PP tape can be woven into broadgoods with various weaving patterns appropriate to the application. The unidirectional E-Glass/PP tape material can also be woven into a plain weave architecture fabric form (Figure 1-2) through textile weaving operations.

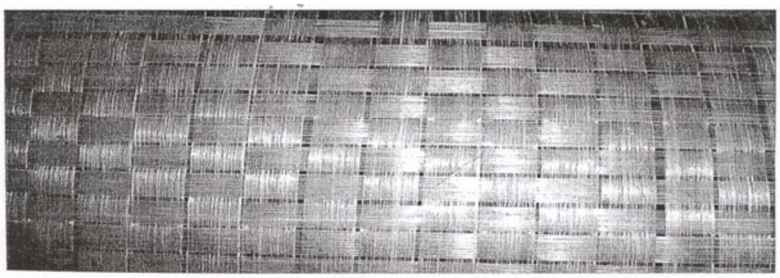

Figure 1-2: Close-up view of woven E-Glass/Polypropylene fabric

Thermoforming is being used to produce large sized plastic components with varying wall thicknesses (greater than 1 mm), formed under low molding pressures (less than 50 psi), with molds made of aluminum alloy, wood, or polymer composites. A simplistic overview of the single sheet thermoforming process consists of heating a plastic (or composite) sheet and forming the sheet over a male mold or into a female one. The operation deforms the sheets of the material into curvilinear shapes with the help of tools and molds. The process uses various configurations such as vacuum forming, drape forming, and matched mold forming. Basic vacuum forming represents the conventional technology: a vacuum is created between a female mold and a heated plastic sheet, which conforms to the mold walls through pressure. Components can also be produced with increasing thickness from the center to the edges. This process involves heating a polymer sheet that is firmly constrained along its perimeter above its transition temperature, forming it into a mold through vacuum, and cooling by conduction in the case of thin films or through fans in the case of thick walls (Vaidya et al., 2004).

## 1.4 Proposed Bridge Deck Shape and Manufacturing of Deck Components

The deck shape for the prototype study was based on a hat-sine rib stiffened design concept and was selected based on considerations such as the processablilty of the thermoplastic Glass/PP woven tape and practical issues such as tooling and design flexibility.

A deck segment shown in Figure 1-3 features a Glass/PP woven tape hat-sine shape ribbed profile bonded to a flat Glass/PP woven face.

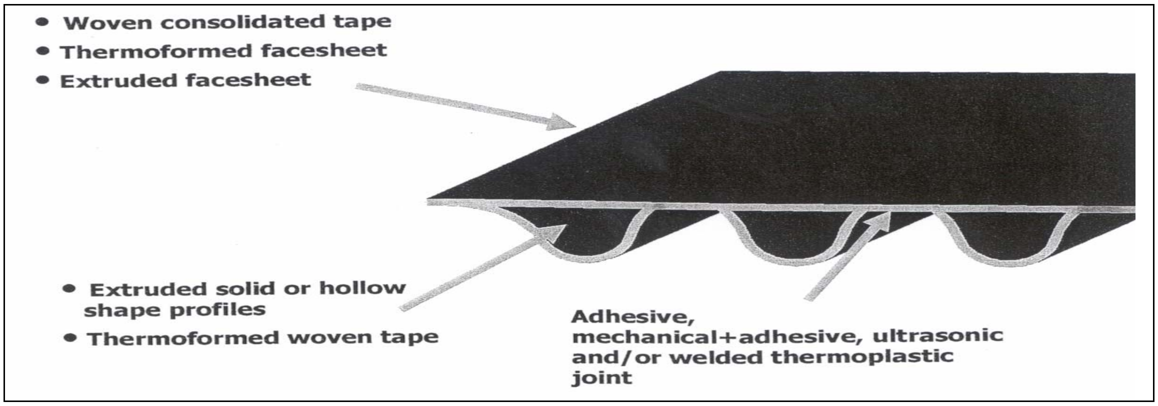

Figure1-3: Hat-sine reinforced deck shape

The face and the rib section of the deck floor can be processed using a number of methods, which include thermoforming, double belt press consolidation of the tape forms, reaction injection molding, and/or extrusion. The contact area of the ribs to the face can be bonded adhesively and or by a combination of adhesive bonding and fasteners.

A three step process was proposed for manufacturing the specific elements of the thermoplastic composite deck floor and is explained as follows:

1. Flat Face Structure: The woven tape material is passed through the double belt press at room temperature, heated, and then compressed under a series of rollers so as to form a sheet.

2. Hat-Sine Rib Structure: The woven tape material is be produced by vacuum thermoforming. For the sinusoidal shape, a tool would be designed and fabricated which accommodates the shape requirements and facilitates heating and cooling during thermoforming. Aluminum tooling has the advantage of machinability and high thermal conductivity which can reduce both cooling and heating time. Steel is the most durable metal for tooling but also the most expensive (FTA Report, 2003). Regardless of the choice of tooling material, the tool itself must be sized according to heating and cooling function so that the respective heat and cool cycles are acceptably rapid.

3. Attachment of Flat Face to Hat-Sine Rib Structure: The face and the hat sine ribs can be adhesively bonded using hot melt glue, however under high production conditions vibration or ultrasonic bonding would be a better solution for assembling the two components.

# Section 2
# Bridge Deck Design Criteria and Analysis Procedure

We adopted the loading conditions and performance limitations described in the AASHTO LRFD Bridge Design Specifications (AASHTO 2000).

## 2.1 Applied Loads

The dead load and the vehicular live load must be applied in different combinations to obtain the maximum effect. The dead load, DC, includes the weight of the structural system, wearing surface, and all attachments. We have assumed 15 psf as the self weight of the deck and 5 psf as the load of the wearing surface, which will be applied as a uniformly distributed load over the surface of the bridge.

The three specified types of vehicular loading, LL are:

1. *Design truck load HS20-44*: three axles with loads of 32 kips, 32kips and 8 kips. The spacing between the 32 kips axles varies from 14 ft to 30 ft and is chosen by the designer to produce the maximum effect for shear, moment, and deflection.
2. *Design tandem*: a pair of 25 kips axles spaced 4 ft apart with transverse spacing of 6ft.
3. *Design lane load:* a uniformly distributed load of 640 lbs/ft applied over a 10 ft wide strip.

The dynamic nature of moving vehicular loads is addressed by imposing an increase on the static loads of the design truck and tandem loads. The dynamic load allowance factor (IM) shall not be applied to pedestrian or design lane loads.

We used the AASHTO category strength I load combination to compute the ultimate capacity (Q) of the bridge:

$$Q = 1.25DC + 1.75(LL + IM) \tag{1}$$

The live load should include either a design truck load combined with a lane load, or a tandem design load combined with a lane load for every lane in the bridge. We used the AASHTO service I loading combination for checking the deflection of the bridge design:

$$Q = LL + IM \tag{2}$$

For maximum deflection and stress, the truck or tandem was placed such that the center of gravity of the truck or tandem is on the center of the bridge, i.e. AASHTO arrangement I. We used arrangement II (with the rear axle of the truck or tandem at one end of the bridge) for the truck and tandem load to check for the critical shear stress.

## 2.2 Deflection Criteria

We used AASHTO specifications 3.6.1.3.2 and 2.5.2.6.2 to adopt the deflection limit of L/800 (where L is the span of the bridge). The specification states that the deflection resulting from the design truck/tandem alone or that resulting from 25 percent of the design truck/tandem taken together with the design lane load should not be greater than the maximum allowed limit.

## 2.3 Strength Criteria

We used the maximum work theory of Tsai-Hill to determine the failure strength of the structure which can be defined by the following equation;

$$(\sigma_1 / \sigma_{1(ULT)})^2 - (\sigma_2 / \sigma_{1(ULT)})(\sigma_1 / \sigma_{1(ULT)}) + (\sigma_2 / \sigma_{2(ULT)})^2 + (\tau_{12} / \sigma_{12(ULT)})^2 < 1.0 \qquad (3)$$

Where $\sigma_1, \sigma_2$ and $\tau_{12}$ are longitudinal, transverse and shear stresses due to applied load, and $\sigma_{1(ULT)}, \sigma_{2(ULT)}, \sigma_{12(ULT)}$ are the ultimate stresses in the longitudinal, transverse, shear direction. These ultimate strength values in checking ply failure using the Tsai-Hill approach are adopted from the literature using experimental results whenever possible.

## 2.4 Analysis and Design Procedure

We used E-glass/PP in the design of the bridge structure. The elastic properties of the laminate for a specific volume fraction of fibers were evaluated; the elastic constants used for analysis are Young's modulus in longitudinal and lateral/transverse direction ($E_X, E_Y, E_Z$), Poisson's ratio in each direction ($\nu_{XY}, \nu_{XZ}, \nu_{YZ}$), and the Shear modulus ($G_{XY}, G_{XZ}, G_{YZ}$). Table 2-1 lists the elastic properties for the composite laminate.

The finite element analysis to model the bridge deck was performed using ANSYS 8.0 software. The composite face and the hat-sine ribs were modeled using the Shell 99 element. The Shell 99 element used has six degrees of freedom at each node constituting the x, y and z direction nodal translations and rotations. Each element is defined by eight nodes (the mid plane and the corner nodes), average or corner layer thickness, orthotropic material properties, and ply orientations. The contact region between the face panel and the hat sine stiffened ribs was developed by merging the common nodes and key points. The loading combinations as defined in section 2.1 were applied and based on the combination of least deflection and corresponding stresses. From this analysis the deck component dimensions (amplitude and wavelength), shape, and thickness were determined.

**Table 2-1: Material properties of E-Glass / PP woven tape composite**

| Property | E-Glass/PP woven tape composite 40 % fiber content by volume |
|---|---|
| $E_X$ | 1437 ksi |
| $E_Y$ | 1437 ksi |
| $E_Z$ | 149 ksi |
| $\nu_{XY}$ | 0.11 |
| $\nu_{YZ}$ | 0.22 |
| $\nu_{XZ}$ | 0.22 |
| $G_{XY}$ | 184.16 ksi |
| $G_{YZ}$ | 108.75 ksi |
| $G_{XZ}$ | 108.75 ksi |
| $E_{FIBER}$ | 10150 ksi |
| $E_{MATRIX}$ | 149 ksi |
| $G_{FIBER}$ | 4350 ksi |
| $G_{MATRIX}$ | 108.75 ksi |

# Section 3
# Design Case Study of Vehicular Bridge

In this section the conceptual design of the bridge deck system is explained through a series of case studies. The design of two deck models with different span lengths and geometric parameters is presented. The first model is a single lane bridge deck with 12 ft width and 6 ft span; the second model is a double lane bridge with 60 ft span and width of 24 ft.

## 3.1 Single Lane Bridge Deck System

We first demonstrated a typical single lane bridge deck having a width of 12 ft and a total length of 24 ft. The deck was supported on three steel girders spaced at 6 ft intervals and was divided into three panels each having an 8 ft length and 12 ft width (Figure 3-1).

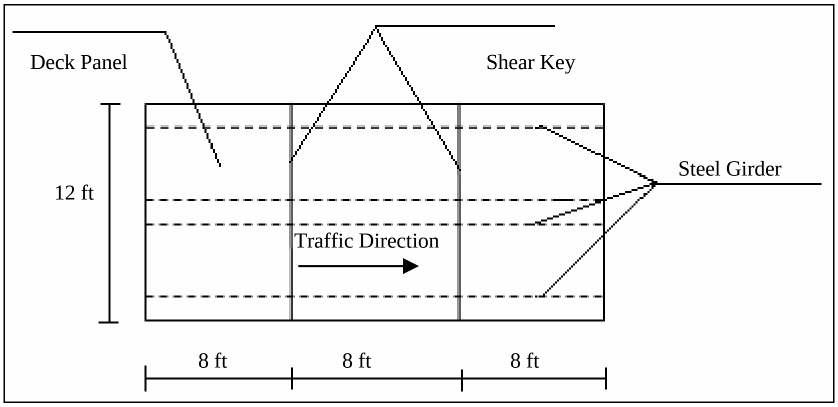

**Figure 3-1: Plan of single lane bridge deck**

### 3.1.1 Design Loads and Allowable Deflection

According to AASHTO (specification 3.6.1.12-1) for a single lane bridge, the live load is multiplied by a multiple presence factor ‘m’ which is equal to 1.2 and by the dynamic allowance which can be taken as 1.33 i.e. 33%. The critical working vehicular loads for a single panel (8 ft by 12 ft) are given as:

1. Design Tandem having 12.5 kips wheel with load dynamic allowance factor of 1.33 and multiple presence factor of 1.2 has factored wheel load:
   P = 12.5 x 1.33 x 1.2 = 19.95 kips
   This point load is distributed according to tire contact area whose width is 20 inches and length is 12 inches for design tandem.

2. Design Lane Load is a uniform pressure of 0.064 kips per square ft. With 1.2 multiple presence factor, it is 0.0768 kips per square ft.

For the live load deflection we can use either the tandem load or the lane load with 25% of the tandem load. The allowable live load deflection is 0.09 inch (Span/800).

According to the AASHTO Strength 1 load combination the critical ultimate loads to check the net stresses are:
Design Tandem Load = P = 1.75x19.95 = 35 kips
Design Lane Load = 1.75 x 0.0768 = 0.134 kips per square ft
Deck Dead Load = 1.25 x 0.02 = 0.025 kips per square ft

### 3.1.2 Finite Element Analysis

The hat-sine shape ribbed profile and the top flat face made of E-glass/PP woven tape ply can be modeled as 0/90 degree layer. The hat-sine ribs were subjected to parametric analysis, which included the amplitude of the hat-sine, the wavelength, and the contact width between the face panel and the ribs (Figure 3-2).

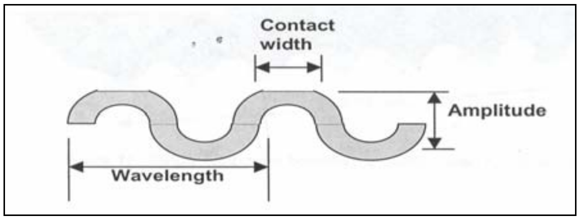

**Figure 3-2: Hat-sine rib design parameters**

After several deck model simulations on ANSYS with appropriate amplitudes, wavelengths, and contact widths, the hat-sine rib dimensions were determined to be optimal at a 12 inch depth, 24 inch wavelength, and 6 inch contact width (Abro, 2006). At this wavelength and contact width we compared the two deck systems by adding an additional bottom layer in the second case as shown by Figure 3-3 and 3-4.

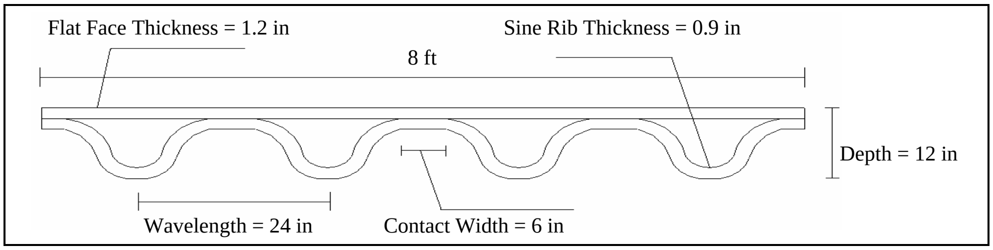

**Figure 3-3: Single lane bridge deck parameters for case 1**

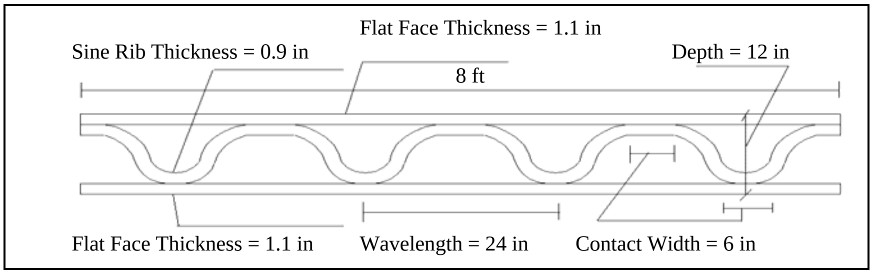

**Figure 3-4: Single lane bridge deck parameters for case 2**

By comparing both shapes we can conclude that the most efficient and cost effective section would be one which has a low cross-sectional area while maintaining sufficient stiffness to control deflection. Based on this criterion, the section shown by case 1 is the optimum section. More results details are discussed in the references (Abro 2006). It has 26.6% less cross-sectional area and will, therefore, result in lower manufacturing costs compared to case 2. The 6 inch contact width was chosen to have an adequate bonding area of the hat-sine rib section to the flat face. For the optimized section (i.e., case 1) the maximum deflection of 0.09 inches is exactly at the point of contact wheel load (Figure 3-5). The maximum ultimate tensile stress of 6392 psi developed at the intermediate support is much less than the failure stress of 28,000 psi for E-glass/PP composite laminate (Figure 3-6). The shear stress due to an ultimate load is 3339 psi and is also within limits (Figure 3-7).

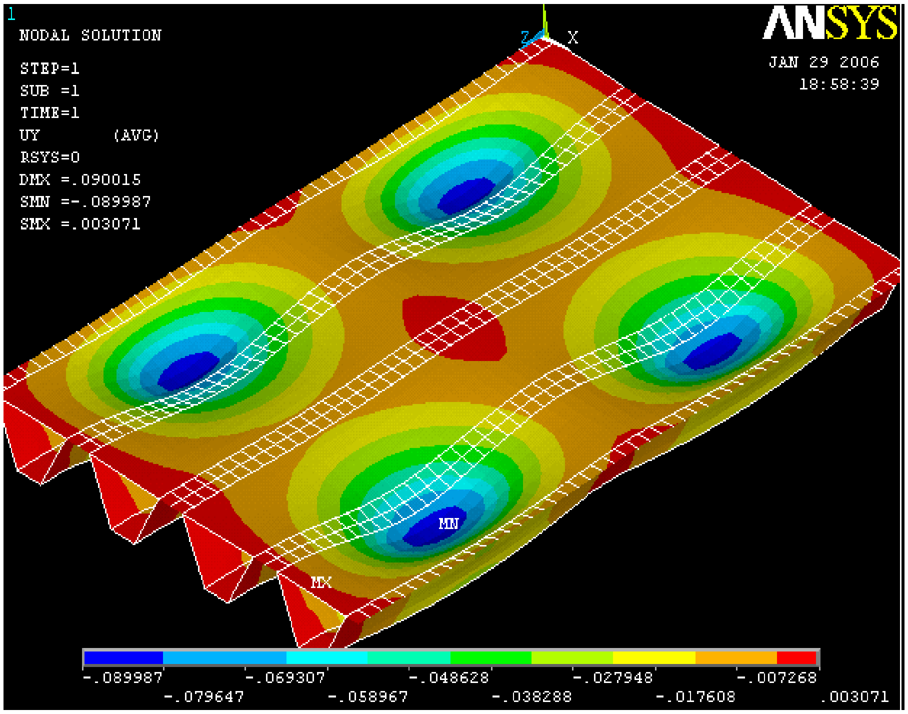

**Figure 3-5: Deflection (inches) for case 1 of a single lane deck model**

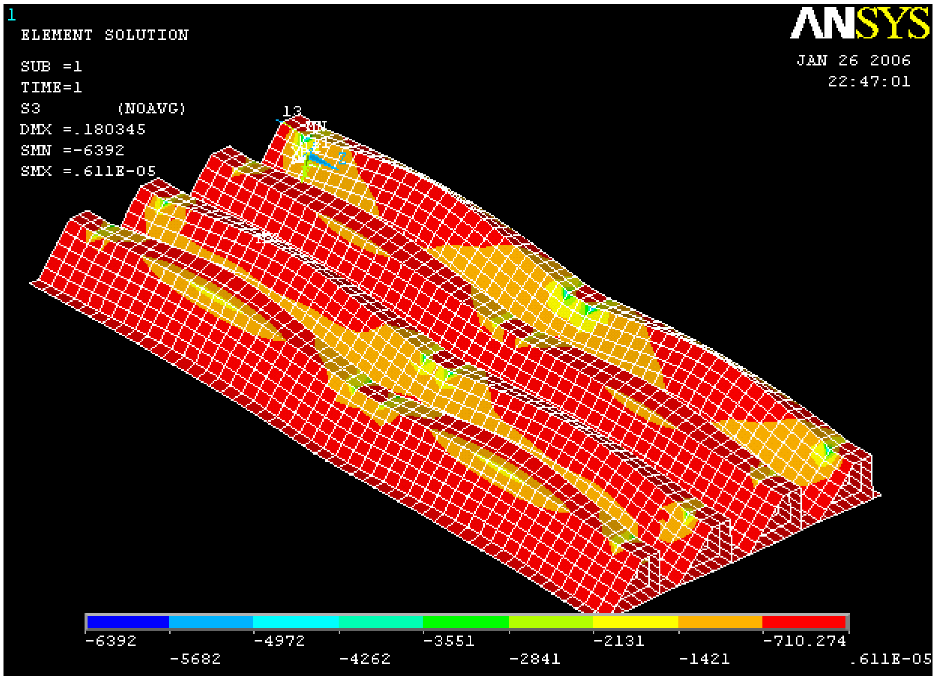

Figure 3-6: Stress profile (in psi) of 0.9 inch thick sine rib for case 1 of a single lane deck model

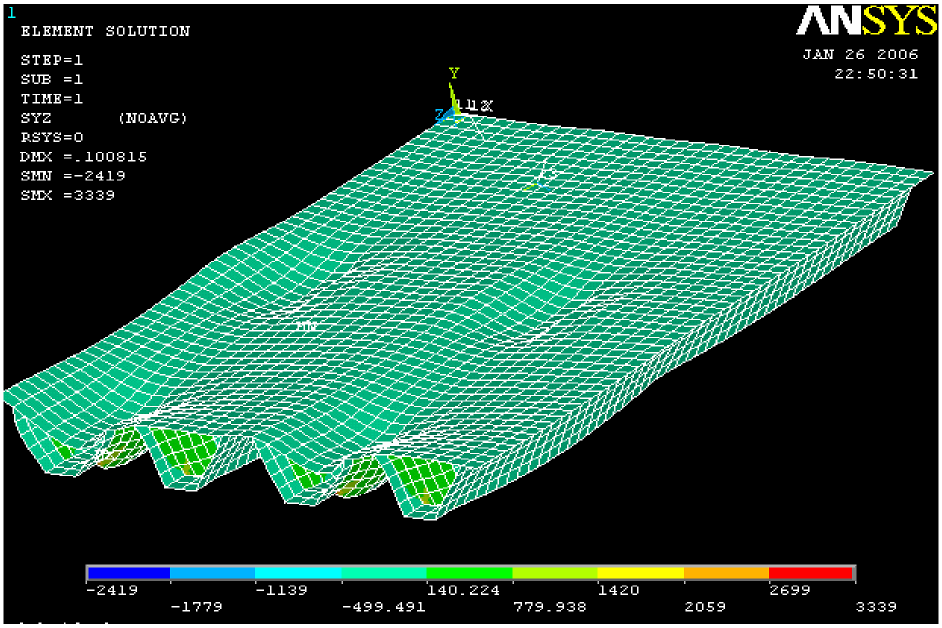

Figure 3-7: Shear Stress (psi) for case 1 of a single lane deck model

## 3.2. Double Lane Bridge Deck System

We further demonstrated the performance of our conceptual design by studying a typical two lane, 60 ft span bridge having a width of 24 ft and depth of 36 in. (Figure 3-8). The length to depth aspect ratio of the deck system is 20:1, which is reasonable for highway bridges.

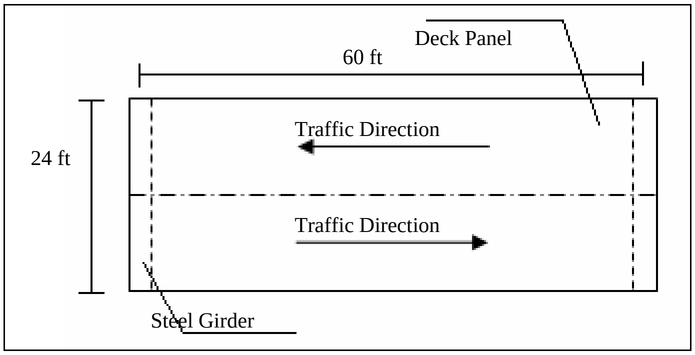

**Figure 3-8: Plan of double lane bridge deck**

### 3.2.1 Design Loads and Allowable Deflection

According to AASHTO (specification 3.6.1.12-1) for a double lane bridge, the live load multiple presence factor 'm' is equal to 1.0 and the dynamic allowance can be taken as 1.33 i.e. 33%. The critical working vehicular loads are given as:

1. Design truck HS20-44 wheel load with dynamic allowance factor of 1.33 and multiple presence factor of 1.0 can be given as
   P = 4 x 1.33 x 1.0 = 5.32 kips (for 8 kip axle)
   P = 16 x 1.33 x 1.0 = 21.28 kips (for 32 kip axle)
   These point loads are distributed according to tire contact area whose width is 20 inches and length is 15 inches for 32 kips axles and 4 inches for 8 kips axle. The spacing between the axles is taken as 14 ft to produce the maximum deflection, shear and moment.

2. Design lane load can be taken as a uniform pressure of 0.064 kips per square ft for each 10ft wide strip of bridge traffic lane.

The allowable live load deflection is 0.9 inches (i.e. deck Span / 800). Using AASHTO Strength1 load combination factors with the load distribution, the ultimate loads are:

Design Truck Load (8 kip axle) = P = 1.75x5.32 = 9.31 kips
Design Truck Load (32 kip axle) = P = 1.75x21.28 = 37.24 kips
Design Lane Load = 1.75 x 0.0644 = 0.113 kips per square ft
Deck Dead Load = 1.25 x 0.02 = 0.025 kips per square ft

### 3.2.2 Finite Element Analysis

Based on the Finite Element Analysis, in this case the hat-sine rib dimensions were determined to be optimal at a 36 inch depth, 48 inch wavelength, and 16 inch contact width (Abro 2006). We further analyzed two deck shape models at this wavelength with a contact width as shown in Figures 3-9 and 3-10.

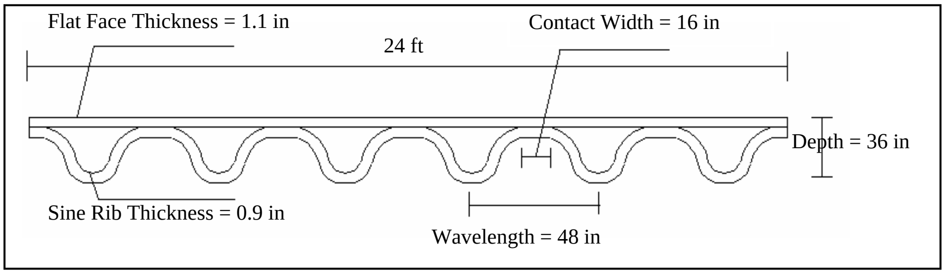

**Figure 3-9: Double lane bridge deck parameters for case 1 using Glass/PP**

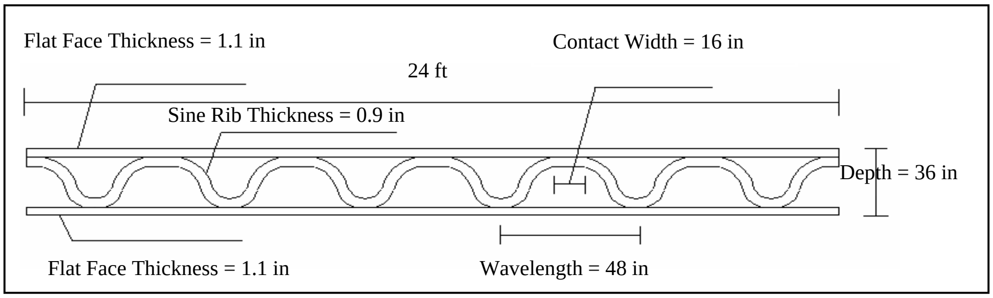

**Figure 3-10: Double lane bridge deck parameters for case 2 using Glass / PP**

The section shown for case 1 was the optimum section because it has 10.33 % less cross-sectional area and will incur less manufacturing costs compared with case 2. More results details are discussed in the references (Abro 2006). The deflection, ultimate flexural stress, and shear stress for the optimized section were 0.9 inch, 6366 psi, and 1710 psi respectively and shown graphically in Figures 3-11, 3-12 and 3-13.

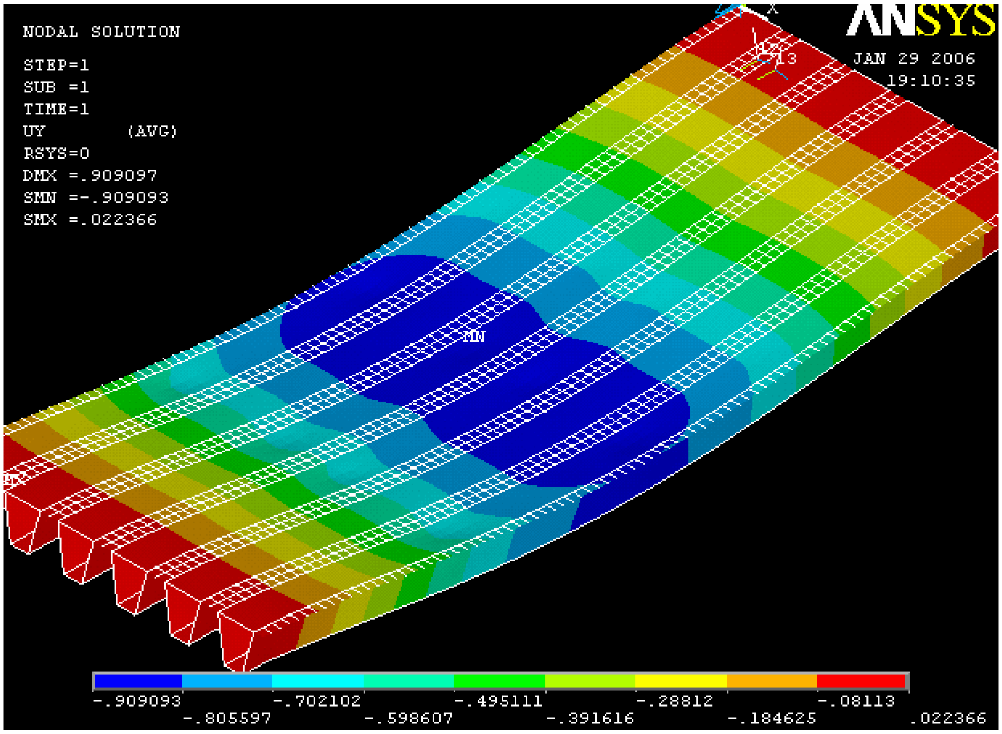

**Figure 3-11: Deflection (inches) for case 1 of a double lane deck model**

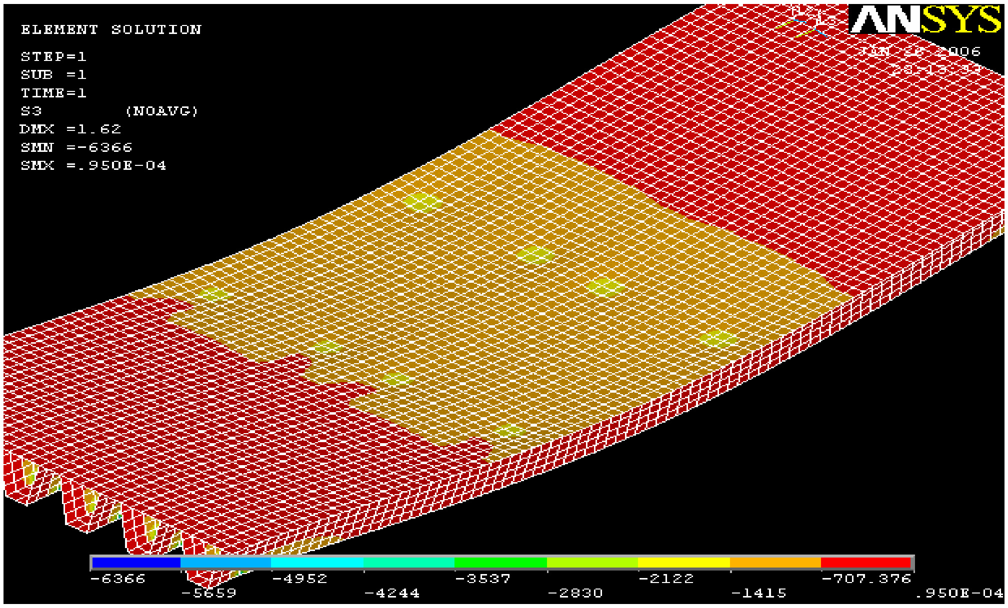

Figure 3-12: Stress (psi) for case 1 of a double lane deck model

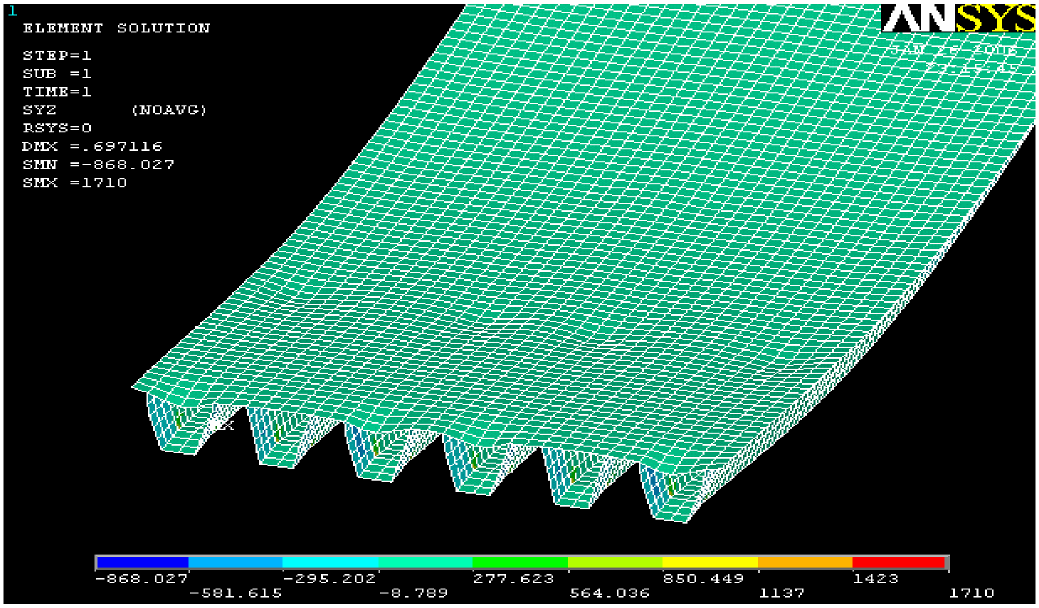

Figure 3-13: Shear stress (psi) for case 1 of a double lane deck model

# Section 4
# Design Verification

For the design verification and analysis of the accuracy of the finite element analysis we compared the results of an experiment in which a panel made from E-glass/PP woven tape was tested under point loads (500 lbs to 2000 lbs). The panel was simply supported and had a length of 43 inch and a 29.5 inch width. Its shape, as shown by Figure 4-1, consisted of a 0.36 inch thick top flat face and a 0.24 inch thick sine curve.

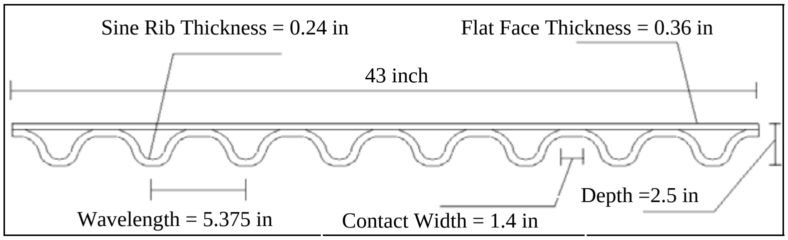

**Figure 4-1: Panel shape and dimensional parameters used in an experiment**

The panel had the material properties as defined in Table 2-1. The experimental setup is shown in Figure 4-2 and more experimental details are discussed in the references (Abro 2006).

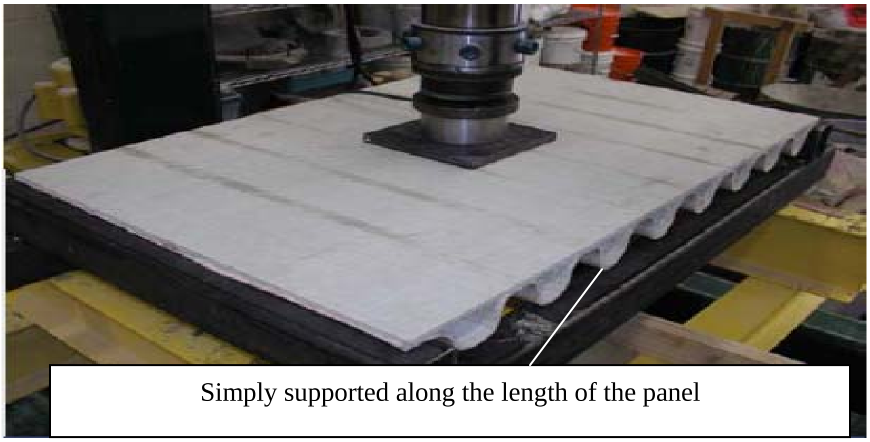
Simply supported along the length of the panel

**Figure 4-2: . Experimental setup to check the deflection of panel**

To check the accuracy of the finite element analysis, the panel was modeled in ANSYS using Shell 99 elements. The support boundary conditions were defined according to the experimental setup and the process of finite element analysis was same as described in section 2.4. The panel model and boundary conditions used in the finite element analysis are shown by Figure 4-3; the panel deflection (due to 1000 lbs load) is shown by Figure 4-4 and the experimental and FE analysis results are presented in Table 4-1.

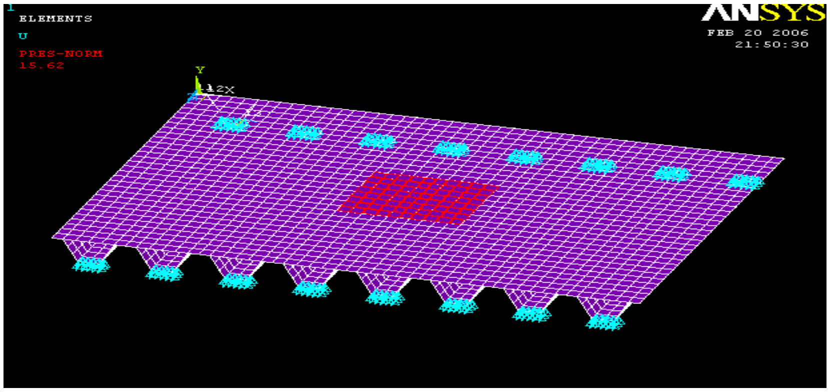

**Figure 4-3: Panel deck model on ANSYS 8.0**

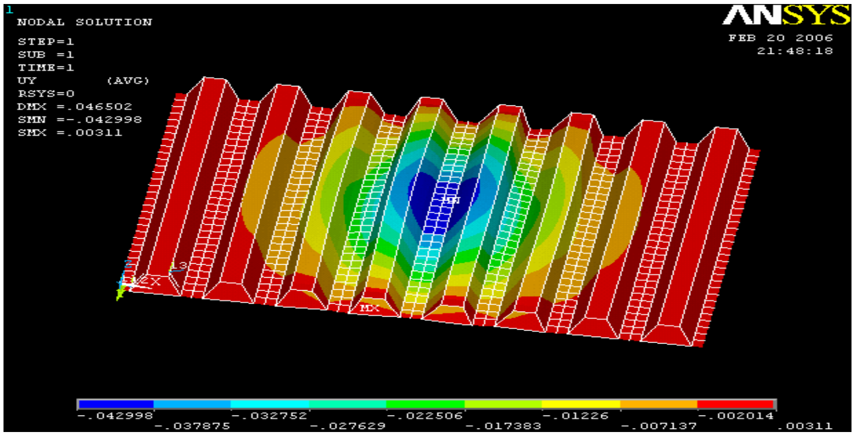

**Figure 4-4: Panel Deflection (inches) using Finite Element Analysis on ANSYS 8.0**

**Table 4-1: Experimental and Analytical Deflection Comparison**

| Concentrated Load (Lbs) | Experimental Max Deflection inches | Finite Element Analysis Max Deflection (inches) | Difference % |
|---|---|---|---|
| 500 | 0.026 | 0.023 | 10.76 |
| 1000 | 0.052 | 0.046 | 11.53 |
| 1500 | 0.07 | 0.06 | 14.28 |
| 2000 | 0.1 | 0.085 | 15 |

By comparing the experimental deflection with the ANSYS analysis (Figure 4-5), the finite element analysis was found to under-predict the deflection by 10 to 15 percent. This difference between the analysis and the model could be due to slight imperfectness in the contact area between the hat sine rib and flat face panel. There might be relative deformation in the prototype experimental model in which the flat panel was bonded to the hat sine rib profile using hot melt glue. This could be avoided by using strengthened bond joining methods such as ultrasonic bonding.

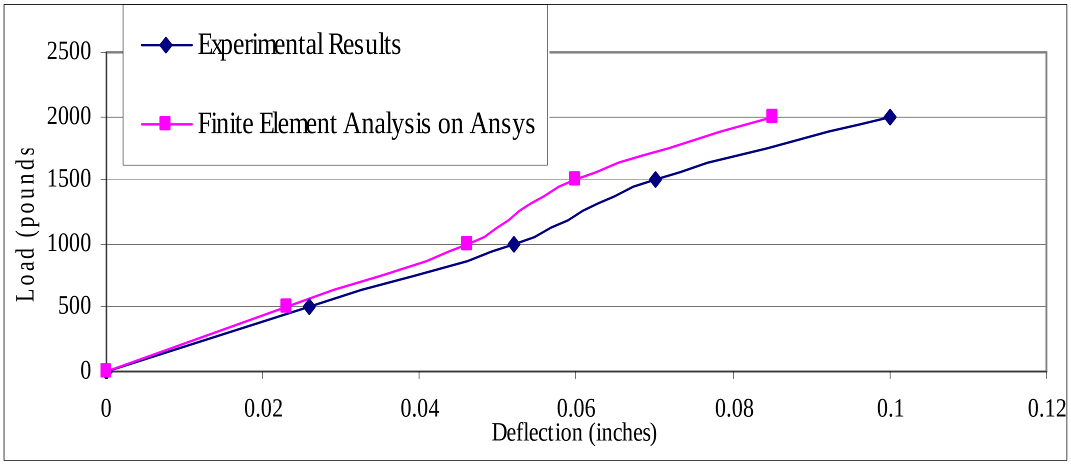

**Figure 4-5: Panel load deflection comparison (experiment vs. finite element analysis)**

# Section 5
# Comparison with other Composite Bridge Systems

We compared the performance of our proposed thermoplastic bridge deck system to two other thermoset designs: a Lockheed-Martin bridge system (Dumlao et at., 1996) and a bridge system proposed by Aref and Parsons (2000).

## 5.1 The Lockheed-Martin bridge

A 30 ft span composite bridge built by Lockheed is described by Dumlao et al. (1996). A schematic of the cross-section of the Lockheed bridge is shown in Figure 5-1 together with our proposed bridge deck design.

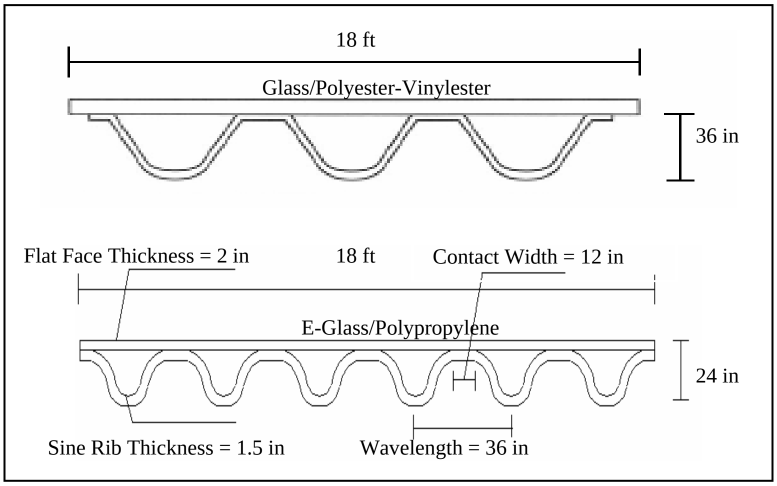

**Figure 5-1: Cross-sections of the Lockheed (thermoset Glass/polyester-vinylester) and the comparison (proposed thermoplastic E-glass/pp) bridge**

The Lockheed design was loaded with a pair of 32 kips axles and exhibited measured deflections less than span/800. We imposed a similar loading condition by using two 32 kips axles with 14 ft spacing. Also the design was checked for a tandem loading condition with 25 kips axles spaced at a 4 ft distance from each other. We studied our optimized design using finite element analyses to obtain the maximum vertical deflection and to study the strength criteria.

The maximum vertical displacement of our proposed design was 0.45 inch, which is equal to the AASHTO limit and occurred under the tandem loading condition. The maximum Tsai-Hill failure index was 0.48 and it occurred under factored loads (strength 1 load combination) using a pair of 32 kips axles with a 14 ft spacing. The interface shear stresses between the outer (top flat face) and inner (sine ribs) shell contact area were $\sigma_{yz}$ = 120 psi and $\sigma_{xz}$ = 366.5 psi. The weight of our proposed design was 28.1 kips and the dead-to-live load ratio was 0.439. The weight of the Lockheed bridge was 23 kips, giving a dead-to-live load ratio of 0.36.

## 5.2 The Bridge Proposed by Aref and Parson (2000)

We compared the performance of our proposed double lane bridge deck system (as discussed in section 3.2) to the bridge system proposed by Aref and Parsons (2000). A schematic of the cross-section of the bridge system proposed by Aref (2000) consists of seven inner cells encased in an outer shell as shown in Figure 5-2 together with a proposed deck system.

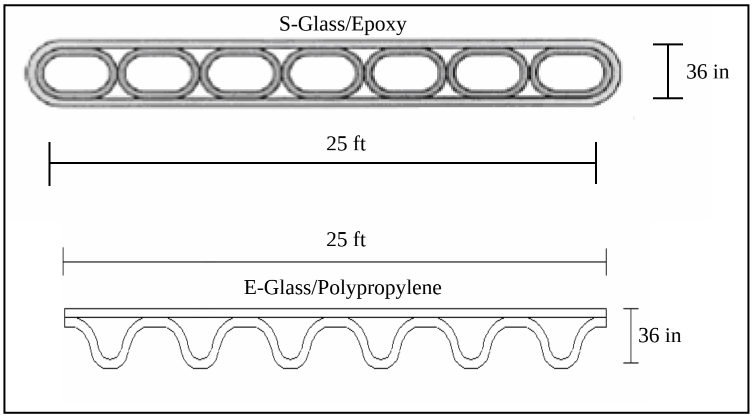

**Figure 5-2: Cross-sections of the Aref (2000) (thermoset) and the comparison (proposed thermoplastic E-glass/pp) bridge**

The performance comparison of both systems is summarized in Table 5-1 based on maximum deflection, failure indices, interface shear stresses, and the self weight of the deck system.

**Table 5-1: . Performance comparison b/w S-glass/epoxy (Aref, 2000) and E-glass/pp (proposed design) deck system**

| Material | S-glass/epoxy | E-glass/polypropylene |
|---|---|---|
| Deflection (inch) | 0.9 | 0.9 |
| Tsai Hill Failure Index | 0.24 | 0.28 |
| Interface $\sigma_{yz}$ (psi) | 504 | 234 |
| Interface $\sigma_{xz}$ (psi) | 484 | 175 |
| Self weight of deck (lbs) | 67,000 | 121,500 |
| Dead load: Live load | 0.46 | 0.84 |

The comparison of our proposed design with the modular fiber (S-glass/epoxy) deck system proposed by Aref (2000) shows similar margins of safety, with Tsai-Hill index values of 0.28 (proposed design) and 0.24 (Aref, 2000). Moreover, in our proposed design a significant factor of safety was achieved in interface shear stresses between the outer (top flat face) and inner (sine ribs) shell contact area. The weight of our design was 121.5 kips, which yields a dead to live load ratio of 0.84. The weight of the S-glass/epoxy deck system was 67 kips, giving a dead to live load ratio of 0.46.

# Section 6.0
# Summary and Conclusions

We have presented design concepts and manufacturing processes for a thermoplastic bridge deck composite structural system. Recognizing the structural demands required to support highway traffic, the deck system was carefully engineered to consider the structural efficiency and the ease of manufacture of the deck components. Glass/PP woven tape material was selected based on its effectiveness in producing structural deck components with flat geometries and gradual radii/curvatures. The deck structural system presented possesses several special features that contribute to its effectiveness, including the use of curved panels (sine ribs) which provide the nonplanar core configurations to increase the performance of the bridge deck system. Based on finite element analysis of several deck models we conclude following points:

1. In all deck design cases, the stiffness was the main governing factor controlling the design. Once the stiffness requirement had been satisfied, the strength of the structure proved to be sufficient. Thus an efficient deck shape should be designed around stiffness criteria and not on strength.
2. In both deck systems (single lane and double lane) a single outer shell (top flat face) with sine ribs provided the most efficient and economical section.
3. By comparing different sections for a 60 ft span bridge deck; we concluded that the most efficient section would be the one which has a low cross-sectional area while maintaining sufficient stiffness to control the deflections. Based on this criterion, a Glass/PP composite section having a single top flat face with sine ribs proved more economical and efficient than one with top and bottom flat faces. The single face panel has 10.33 % less cross-sectional area and a lower manufacturing cost.
4. The deck analysis methodology based on finite element modeling using ANSYS 8.0 software yielded results close to those obtained experimentally for the modular type fiber composite deck system. The finite element model showed a variation of 10% to 15% compared to the experimental data. These differences could be reduced by more closely defining the experimental conditions.
5. We compared our design to two published composite bridge concepts proposed by Dumaloa et al. (1996) and Aref (2000). Although our design has a higher self weight which results in a higher dead to live load ratio than the alternative designs, our design could result in a better low cost deck section based on the manufacturing and material cost comparisons. E-Glass/PP is much less expensive than S-glass and the manufacturing process associated with it yields cost effective results under higher production rates. Thus the actual comparison between bridge deck designs should be based on the construction cost of the bridge deck systems. This cost is dependent on two main factors, i.e., the cost of the constituent materials in the system (fibers and polymer matrix) and the cost related to the manufacturing of the structural system. Detailed cost analysis directed towards the manufacturing process and bridge deck materials is required before any definitive conclusions can be made regarding this issue.

# Section 7
# Future Research

Recommendations relevant to the structural system described in this report and to the design procedures in particular are outlined in the following points.

1. The bridge design presented in this study is mainly governed by stiffness. The stiffness of the bridge system may be enhanced by prestressing. Strands extending through the hollow areas between cells could be used to create camber and reduce the deflection of the bridge.
2. The temperature or hydrothermal effects were not included in this study. Depending on the curing process, residual stresses may exist in the structure at various intensities. During the life cycle of the bridge it will be subjected to various environmental conditions and the induced stresses due to water absorption should be investigated to understand bridge behavior and devise means to limit any damaging effects.
3. The dynamic nature of the loading dictates extensive study of the effects of fatigue on the bridge system. Attention should be given to the areas where the cells are in contact. The bridge system should be tested under cycling loads for various stress levels.
4. Thermoplastics are more sensitive to creep than thermosets, thus their creep factor must be taken into account.
5. The durability of thermoplastic decks when subjected to various environmental factors must be examined. Other factors, such as flammability and method of repair are other important issues which may be studied for better and improved deck systems.
6. Manufacturing and fabricating issues for very stiff thermoplastic composites with high fiber content must be studied. The environmental and thermal resistance of thermoplastic composites with very high fiber content is also an important issue which needs significant attention.

# Section 8
# References

AASHTO.(2000). “Standard Specifications for Highway Bridges”, 18th Edition, Washington D.C.

Abro, A.M., (2006). “Design and Analysis of Thermoplastic Composite Bridge Superstructures,” MS Thesis, CCEE Department, University of Alabama at Birmingham, Birmingham, AL.

Aref, A.J., and Parsons, I.D. (2000). “Design and performance of a modular fiber reinforced plastic bridge.” *Journal of composites,* Part B 31, 619-628.

Center for Composites manufacturing report (2003). FTA Report Number FTA-AL026-7001-2003.1.

Dumlao, C., Lauraitis, K., Abrahamson, E., Hurlbut, B., Jacoby, M., Miller, A., and Thomas, A. (1996). “Demonstration low-cost modular composite highway bridge”. *Proceedings of the First International Conference on Composites in Infrastructure*, 1141-1155.

Husman, G., Hartness, T., Koeing, J., and Dyksterhouse, J. (2001). “The characterization of low cost fiber reinforced thermoplastic composites produced by the DRIFT process”. *Composites*, Part A 32, 1155-1160.

US Department of Transportation. (2000). Federal Highway Administration.

Vaidya, U., Pilley, S., Janowski, G. (2003) “Tensile response of long fiber thermoplastic composites”. *Developments in Theoretical and Applied Mechanics*, volume XXII.

Vaidya, U., Samalot, F., Pillay, S., Janowski, G., Husman, G., and Gleich, K. (2004). “Design and manufacture of woven reinforced glass/polypropylene composites for mass transit floor system.” *Journal of Composite Materials*, volume 38, no. 21, 1949-1972.