Bridge Engineering

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The scope of the Transportation Research Board's (TRBs) Committee on General Structures includes factors affecting the physical behavior, service life, economy, appearance, and safety of bridges and structures for transportation systems, and accounting for these factors and their interactions in design procedures and criteria. During the ٢٠th century the United States has essentially created the safest, most efficient, and most effective highway and intermodal transportation network in the world. The challenge for the new millennium will be to further enhance this transportation network. In this paper the status of bridge engineering at the end of the ٢٠th century in the area of general transportation structures is summarized. The focus is on bridge structure types, design aspects, new materials, aesthetic concerns, and key policy issues. An attempt is made to forecast the status of bridge engineering ٢٠ to ٣٠ years into the next millennium; the paper is written as though these forecasts will become a reality.

BRIDGE STRUCTURE TYPES

Structure types have been evolving throughout history. The evolution will continue into the future, perhaps at an accelerated rate.
The driving forces behind continued advances in bridge engineering are traffic congestion and costs. In the future, just as now, the public will expect few traffic delays, if any. They will want transportation costs to be as low as possible. Computer technology will enhance traffic management so well that the public will become accustomed to flowing traffic and more aware of congestion locations. Disruptions from construction will be more obvious and even less tolerated. Given these conditions, structural types will be selected primarily on the basis of speed of construction to minimize traffic delays. Low maintenance will be a must, and the ability to widen a structure easily and quickly will be a priority in selecting a structure type.
Safety and aesthetics will continue to play major roles in the selection of structure types. Keeping substructures out of the roadway clear zone will dictate longer span lengths and will keep the engineering community striving for optimal spans. Input from the public will grow to such a level that interactive design programs will become a necessity. Computer programs that automatically prepare detailed plans incorporating changes at the touch of a button will allow the public to modify or add aesthetic details right up to the point that construction begins.

Long Span

Posttensioning with high-strength materials will allow traditional concrete and steel bridges, especially box shapes, to reach continually longer spans that challenge steel truss bridges and even the shorter-span cable-stayed bridges. Cable-stayed bridges and suspension bridges will most likely continue to dominate the long-span bridge category. Long-span bridges will continue to be the most dramatic, capturing the public's awareness with highly visible and innovative structures. Shown in Figure ١ are two impressive structures, the Sunshine Skyway Bridge and the Houston Ship Channel Bridge, which is the longest concrete box to date.

Medium Span
Medium spans include spans from ٥٠ to ٢٠٠ feet and traditionally have been prestressed concrete girders and steel girders. In the future, new materials with high-performance characteristics will be developed, and the strengths of concrete and steel materials will be enhanced. Stronger materials and innovative design concepts will come together to yield much longer spans. The result will be simpler structures with fewer substructures and a reduction in overall cost. Space frame structures using steel and concrete in combination may enter this market because of ease of construction and relatively low cost. Preengineered, "out-of-the-box," prefabricated component bridges will also become more common and will begin to challenge individualized designs. Innovations will cause greater change to the medium-span range than to the other two ranges. An innovative steel bridge that clear-spans an entire freeway is shown in Figure ٢. Bridges that clear-span roadways will become popular in the future.

Short Span
Concrete slabs, timber slabs, prestressed concrete shapes, and rolled steel shapes currently share the market for spans up to ٥٠ feet. In the future, these types will be challenged by long-span culverts and preengineered, out-of-the-box, prefabricated component bridges. Shown in Figure ٣ is a typical long-span culvert (٤٤-foot span) that is starting to challenge more typical short-span structures.

DESIGN
Designing bridges according to a standard specification became the norm in the ٢٠th century. This will continue in the next century. However, the process of designing will be much different in the future because of changes in specifications, loads, testing, and computerization.

Specifications
The specifications used for structural bridge design at the end of the ٢٠th century are split between the American Association of State Highway and Transportation Officials (AASHTO) load factor design (LFD) specification and the load and resistance factor design (LRFD) specification, with LRFD recently being designated as the standard for the future. LFD will continue to be used for some time, but its usage will decline as LRFD becomes more widely accepted. Eventually LFD will be discontinued and LRFD will be fully adopted, which will prove to be the right course of action. The AASHTO LRFD specification will continue to evolve with new research, new design ideas, and new

materials. The LRFD method will prove to be effective and will be easily adapted to all construction materials including steel, concrete, timber, and the new high-strength plastic polymers.

Acceptance of the LRFD method by the design community will not be easy because of concerns in two areas: substructure design and computer software. One goal in establishing the LRFD specification was to provide a more uniform level of reliability in every component of the structure, from substructure to superstructure. The design of substructures using the LRFD philosophy will remain in an immature state for several years because of a lack of accepted methods for analyzing and designing foundations. Only after more research and specification enhancement will the situation for substructures change. Widespread usage of LRFD will be somewhat slowed by the lack of computer software. The detailed nature of LRFD code requires that designers develop spreadsheets and other computer worksheets to complete computations efficiently. Introduction of programs such as the AASHTO OPIS computer program will help, but the full benefit of the new design code will not be realized for several years.

Loads

At the heart of the load specification is the design vehicle. The old HS-٢٠ truck, which has been in use since ١٩٤٤, is being questioned as a vehicle relevant to traffic needs of the ٢١st century. Early in the century, two specific questions will arise over the continued use of this vehicle. The first question is whether a different vehicle would better match the weigh-inmotion (WIM) data coming from the monitoring systems installed in roadways. Though the data are of questionable accuracy, they indicate definite trends—that truck lengths, weights, and traffic counts have increased dramatically since the arrival of the HS-٢٠ truck.
The second question is whether another vehicle would simplify computations. Various factors and loading conditions were applied to the HS-٢٠ truck to make it fit the LRFD specification. In consideration of these two questions, a new “millennium truck” live-load configuration will be proposed. After extensive data collection, the testing and monitoring will begin.

Field Testing

To help determine an appropriate design vehicle, a more comprehensive system of WIM sites will be installed. Because of advances in accuracy and durability of the equipment, dynamic load data will begin to agree with static load data. An accurate picture will then develop of actual truck axle loads and axle spacings on highway bridges. Emerging technologies such as quartz sensors and fiber-optic enhancements, along with piezo cable, will make more accurate data collection possible. Smart bridges will be the order of the new millennium because of a dramatic increase in the number of instrumented bridges. Actual stresses will be measured and tracked in much the same way as the National Weather Service tracks daily temperatures. The WIM information will be correlated with the information from the instrumented bridges. Analysis of the massive amounts of data will be possible through the use of high-capacity computers. The LRFD design load factors will be updated on the basis of the new data.
Steel structures will especially benefit from instrumentation and field testing. In response to fatigue and associated problems, steel bridges will be instrumented to determine failure mechanisms, especially crack initiation at low stress ranges with large numbers of

loading cycles. Emerging technologies will lead to the discovery of relationships that will bring about a refinement of design methods. Cost-effective retrofit applications for fatigueprone details will lead to a change in bridge management planning for bridges with fatigue problems. As this knowledge increases, steel bridges will be replaced mostly for functional rather than for structural reasons.

Analysis

Computer programs capable of analyzing large amounts of data will be developed. Key design parameters such as distribution factors, multiple presence factors, and uniform loads will be verified. Trends in loadings and the way structures respond to those loadings will be made easier to predict. This may lead to a simplification of design factors and equations, which will allow a drastic improvement in the speed of completing design computations. The design of bridges in the ٢١st century will be much easier and more accurate than at the end of the ٢٠th century.

Design Tools
More and more states will cooperate in the use of standardized details, computer programs, and drafting details, making designs and plans more similar on a regional basis. Such standardization will tend to reduce construction costs for contractors and suppliers. Speed and accuracy will be increased.
After many years of working separately, computer-aided engineering and computeraided drafting will be successfully integrated. Designs and plans will be iterative and interactive, and plan preparation will be extremely cost-effective. Design engineers will be alerted by automatic specification checkers and code verifiers, enabling them to minimize design errors. More important, optimization of a design will be a keystroke away. Artificial intelligence will supplement institutional memories and expand designers' options for obtaining real-time expert advice. The need to develop expert systems to check the accuracy and reliability of design software will be a challenge to bridge design professionals. Of course, associated with this challenge is the ever-present debate on professional liability.
Automation
The Internet and e-mail will be standards for communication between designers, fabricators, and contractors. It will become more common for designers and drafters in different states to combine efforts. Correspondence will be handled electronically, eliminating the time necessary to print and mail correspondence back and forth. Contractors and fabricators will view the final plans electronically.
Materials
Materials have always played a key role in the evolution of bridge structures. Enhancements of the traditional materials of concrete, steel, and timber will continue, but the most revolutionary changes will occur in the areas of fiber-reinforced plastics (FRPs), highstrength and high-performance steel, high-performance concrete (HPC), and the blending of FRP and timber.

FRPs
Today, FRPs are in their infancy as bridge construction materials. However, further experimentation with various combinations of FRP materials will result in innovative and long-lasting solutions to simple and complex bridge construction issues. Experimental FRP bridge projects have shown that this material has inherent problems in deflection, material ductility, creep, reactivity with concrete and steel, and performance under long-term exposure to ultraviolet light and other environmental factors such as moisture, freeze-thaw, humidity, and external chemical attack. To help resolve these issues, material testing standards and design methodology will be developed to fit FRP material properties. A comprehensive research effort at the national level will be undertaken to make FRP a dependable, low-maintenance bridge material capable of delivering high performance over the life of a bridge structure.
Collaboration of practicing designers, construction engineers, and bridge owners will make FRP a feasible and competitive alternative to conventional bridge construction materials. Universities will most likely expand their curricula to include FRP and other composite materials in their structural and material courses to prepare future bridge professionals to accept and fully utilize FRP.
High-Strength and High-Performance Steel
Unlike FRP, high-strength steel materials will be more readily accepted by bridge engineers. Initial acceptance will be gained because the new steel materials make it possible to reduce structural dead loads. Wider acceptance of high-strength steels will develop because of their enhanced material properties. Gains made in improving material toughness and weldability of high-strength steels will extend to all grades of steel. Design specifications will continue

to be updated to deal with material performance issues such as welding, toughness, fabrication, and constructibility. The high-performance steel materials of today will become the standard for future construction.

Advances in construction and experimentation with bridge types, such as space frames and innovative composite structures, will lead to further optimization of steel materials. FRP combined with high-strength steel has high potential for future bridge structures.

High-performance reinforcing bars will become common in the new millennium. Composite bars with a steel core and a cladding of stainless steel or other noncorroding material will gain wide acceptance for use in concrete structures. Coupled with the use of HPC in bridge decks, the average life of such structures may approach twice the life span of similar structures built previously. Future national policies requiring life-cycle cost analysis will provide a large incentive to further develop and implement the use of innovative materials in bridge decks.

HPC

HPC is well on its way to becoming a conventional bridge construction material as a result of Strategic Highway Research Program research and Federal Highway Administration implementation efforts. The debate as to whether strength or permeability is the primary indicator of long-term durability of HPC will continue among practicing engineers. However, past case studies clearly demonstrate the need for permeability tests as an indicator of long-term concrete durability. The future is bright for HPC because it has good durability and strength characteristics, making it a versatile material. Currently, assessment

of long-term durability is an after-the-fact determination, resulting in quality control/quality assurance problems, which hamper the use of performance-based specifications. Scientists and engineers will eventually develop a device that instantaneously predicts the long-term durability properties of hardened concrete by testing the concrete in an unhardened state.

Timber

New processes of reinforcing wood will continue to be developed, including the combination of glued-laminated timber and FRP composites. The concept is similar to that of reinforced concrete; wood resists the compression load, while FRP composite resists tensile load. The concept will be commonly used in future timber structures. Advantages of this technology are in areas where bending strength controls the design (as with lower grades of wood). Reinforcing with FRP greatly increases the tensile capacity of the beams, which will allow lower grades of wood to be used economically in many structures. The new composite material will also be used where minimum clearance is a problem.

Breakthroughs in the area of wood preservatives will continue. They will result in the development and refinement of new alternative treatment processes and procedures that will be environmentally sound with respect to application, use, and disposal of treated timber.

Other Materials

A significant future challenge for the construction industry will be the incorporation of recycled materials (including plastics), by-products, and waste materials into conventional and HPC construction materials. Future environmental regulations and lack of space to store waste products will bring this issue to a head. Significant time and financial resources will be spent in developing recycled materials into products suitable for use as construction materials.

A Heavy Duty Composite Bridge Made of Glass/ Polyester Pultruded Box Beams

Abstract
The present work deals with the design and construction of a vehicle bridge made of glass reinforced polyesterpultruded box beams.
The bridge is of ١٢ m span and ٤m width and represents a single strip-loading lane. The load bearing capacity of the bridge is ٣٠٠ kN and an overall design factor of ٣ has been used. The composite bridge
is consisted by a ٣-D truss structure made of two layer one-shot, thick wall FRP longitudinal box elements of hollow square cross section, which are bridged together with box-beams of the same geometry.
A continuous monitoring of the structural integrity of the composite bridge has been scheduled by using vibration analysis techniques and periodic Acoustic Emission monitoring. The total weight of the composite bridge does not exceed the ١٣٥ kN while its expected service life is ٥٠ years.

Introduction
The use of low cost composites in construction consists a major challenge for both the engineers and the Plastic Industry. Although composite materials behave in a completely different manner in constructions compared to the traditionally used materials (cement and steel) and do not offer the large
plastic deformation zones, they have a number of advantages such as high specific stiffness and strength, excellent corrosion resistance and low maintenance cost, which under certain circumstances make them very attractive for applications in construction industry. These advantages have motivated several research groups to consider Fiber Reinforced Plastics (FRP) as an alternative material for bridge construction.
The application of FRP materials in bridge construction industry may be divided in [١]
- Retrofitting schemes to repair and upgrade bridge components [٢,٣],
- Design of replacement bridge components [٣-٥] and
- Design and construction of new bridge structures either for pedestrians or highway applications fabricated from FRP [١, ٦-١٠].

During the last decade FRP bridges have become increasingly popular. At first, mainly bridges for pedestrians and light traffic were designed and built. Recently, also heavily loaded bridges have been accomplished in FRP. Among them the first FRP bridge that carries trucks in UK with an ٨.٢ m span and ٤.٣٤ m width crosses the Stroudwater Canal [٧] and the Lockheed Martin Corporation bridge [٦],

having a ٩.١٤ m span and a carrying load capacity of ٤٤٤.٨ kN, which is made of pultruded panels that
form the bridge deck and are attached to three U-shaped girders with mechanical fasteners.
Among the FRP manufacturing processes for the building up of large beam like structures the most industrialized and attractive one is the pultrusion, which imposes the fewer restrictions on the designer when developing pultrusion shapes, offers an almost constant cross section and can be pulled continuously up to a product length which limited only as to what practical to transport.
The present work deals with the design and construction of a highway bridge made of glass reinforced polyesterpultruded box beams.
The adopted design concept relies on already existing concept for truss metal structures. However the modular design of the structure, the fully industrialized production of its structural elements, the easy way of assembly and the lightweight of the final bridge place the present proposal among the attractive
alternatives for future applications.
The bridge is of ١٢ m span and ٤m width and represents a one strip-loading lane. The load bearing capacity of the bridge is ٣٠٠ kN.
The composite bridge is consisted by a ٣-D truss structure made of two layer one-shot longitudinal box elements of hollow square cross section, which are bridged together with box-beams of the same geometry.
The beams are joined together by using a specially design metal connector node, which secures the proper immobilization of the truss nodes. Figure ١ shows an overall view of the ٣-D truss bridge structure. After the initial analysis of the structure and the choice of ٣-D geometry in order to meet the

imposed restriction of maximum permissible deflection of the structure d_{max}< L/٨٠٠ (L is the bridge span), a detail analysis and optimization of the structure and the metal connector nodes has been performed numerically.
The bridge deck is made again of glass reinforced polyester beam elements of two different cross sections, which have been placed and immobilized on the bridge in the transverse direction. Adhesive bonding and mechanical fastening have been used in all the connections of the ٣-D truss frame and of the deck. The top-wearing layer of the deck is consisted of ١٢ mm polyester cement. Special care has been taken for the easy assembly of the bridge, which minimizes the need of experienced personnel and time.
A continuous monitoring of the structural integrity of the composite bridge has been scheduled by using vibration analysis techniques and periodic Acoustic Emission monitoring. The total weight of the composite bridge does not exceed ١٣٥ kN while its expected life is ٥٠ years.

Design concept

The proposed bridge design is a ٣D truss made from FRP pultruded box beams and steel joint nodes. The truss design although conventional, is perhaps the best way to provide a structure with increased bending stiffness, while sparing material. Being a widely used principle in constructions, especially for
structures intended to cover large spans, the truss can be quickly and easily analysed by existing FEM codes used in civil engineering applications. In addition, the actual building up of such a structure is more or less a standard procedure for construction industry, requires a simple work-site and it is far lesslabour intensive compared to other, more elaborate designs using composites. The visual inspection of almost every part of the structure and the capability to use sophisticated tools for continuous health monitoring of the structure is also possible. However, the main reason of adopting a truss design is that allows for the use of simple, massively produced components, such as beams made bypultrusion. In fact the box beams required for this truss design are small enough to be manufactured using a small/medium pultrusion machine. Alternative design concepts, such as the “deck on girder beams” design, were examined but they required very large profiles that can only be manufactured in specialized facilities.

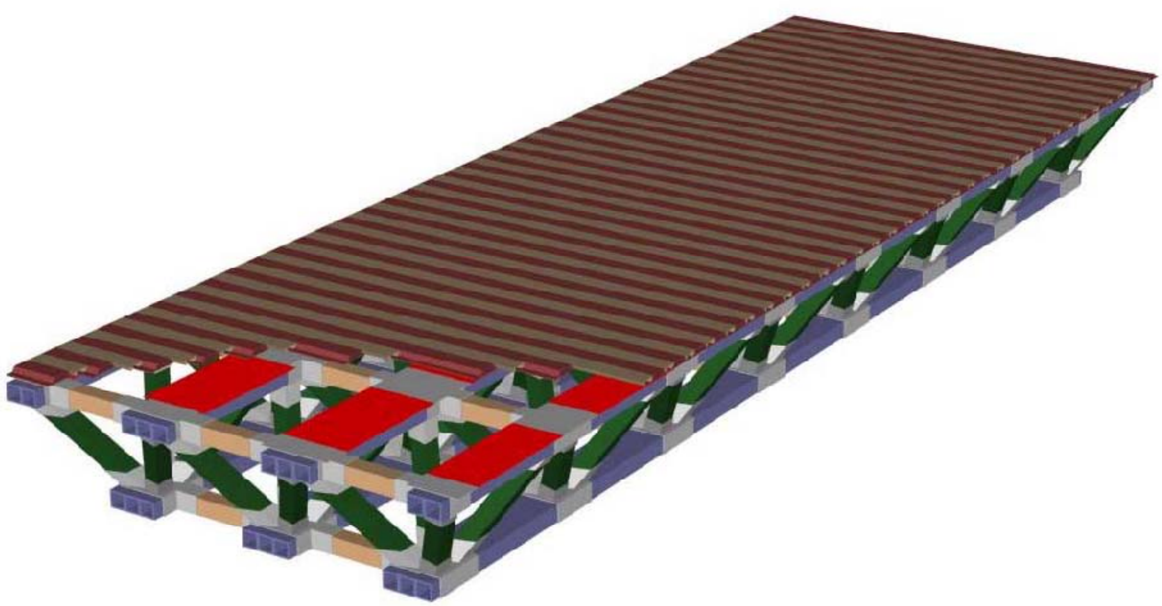


Figure ١: ٣D representation of the bridge design concept
The bridge design concept is presented in Figure ١. It consists of two layers of longitudinal beams

forming seven larger “composite” beams, interconnected with a series of beams of the same cross sectionutilising a number of joints that act as the nodes of the truss as shown in Figure ٢. Between the joints, a set of transversely placed box beams provides extra stiffness and lateral stability to the structure. On top of the truss, a deck structure comprising of two kinds of pultruded profiles is assembled to the rest of the bridge using adhesives and mechanical fasteners (Figure ٣). Finally, the top-traffic surface is made of polyester cement, suitable for heavy vehicles.

Both adhesion and mechanical fastening secure the assembly between the metal joints and the pultruded FRP box beams, in order to guarantee a fixed connection. Each bonding method is designed to independently withstand the operation shear loading, thus realising a fail-safe mechanism.

The proposed design can be considered as a modular one, regarding the subassembly of the joint node and its beams as the module component. This way the width can be adjusted by changing the number of modules width wise.

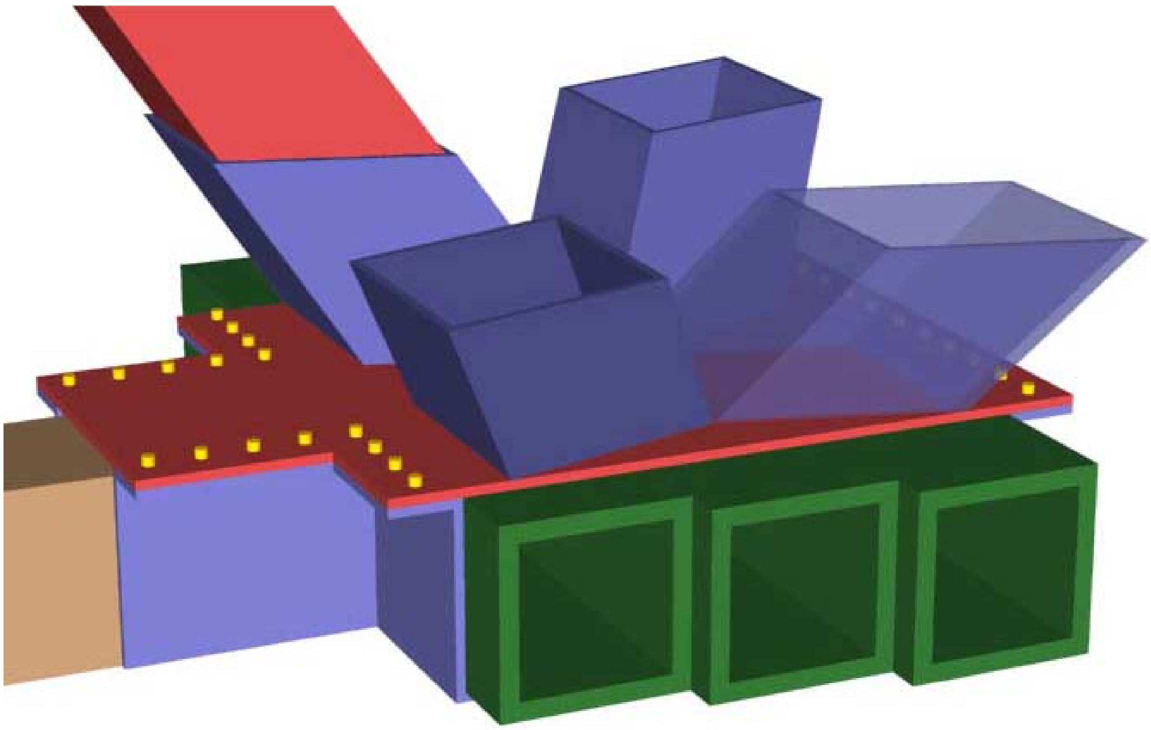


Figure ٢: ٣D representation of the joint assembly with the box beams.

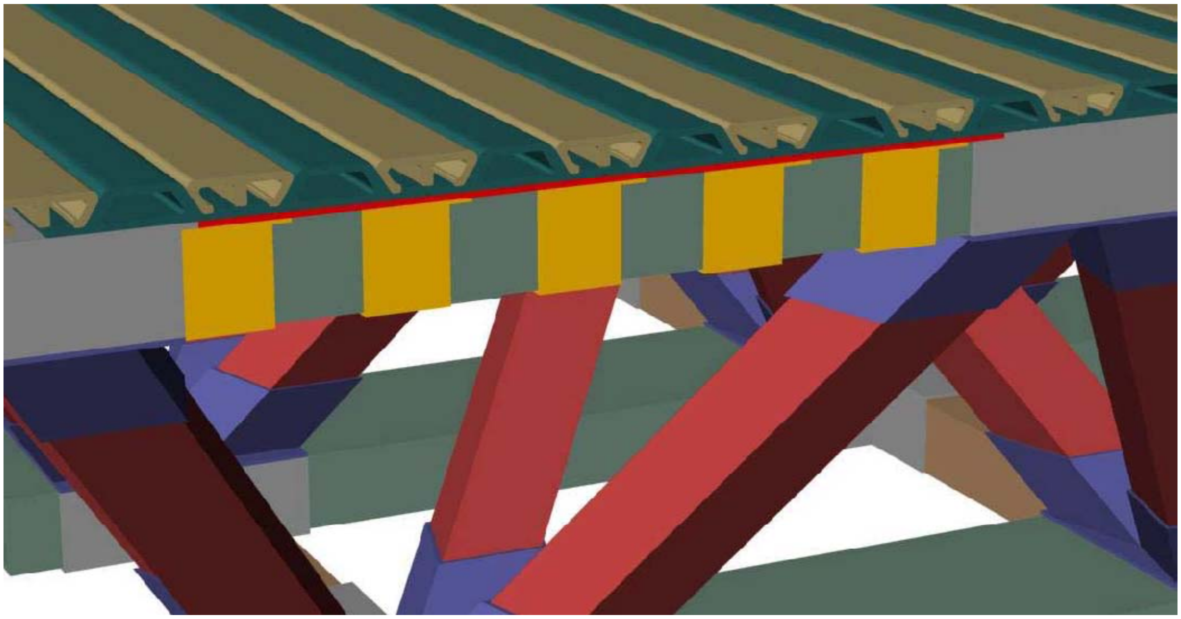


Figure ٣: Detail of the structure showing the deck anchoring on the truss.

In order to increase the span of the bridge, an increase in the height of the structure is required, which can be achieved by increasing the length of the beams that connect the two layers of longitudinal beams. It is therefore possible to apply this design concept for a variety of situations, since the actual dimensions of the bridge can be adjusted by changing the length of the FRP beams.

Design criteria

The design concept described above was implemented in the construction of a prototype bridge superstructure. Therefore it was decided to design and construct a simply supported highway bridge having a ١٢ m span and ٤ m width, which corresponds to a single traffic lane. Loading conditions and performance limitations imposed by DIN ١٠٧٢ for bridge design specification was adopted. The vehicular live load, assumed to be ٣٠٠ kN, must be applied in different possitions on the bridge in order to identify the maximum loads. The dead load, which includes the weight of the structural system, the wearing surface, the barriers and all the attachments except the metal connecting nodes was considered uniformly distributed over the surface of the bridge, while the dead load of each metal node has been considered at its own position.

The dynamic nature of moving vehicular load was addressed by imposing an increase on the static load of the design truck as described in the DIN ١٠٧٢. In addition, the maximum allowed deflection of
L/٨٠٠ (where L is the bridge span) specification was adopted. Since the imposed maximum deflection limit leads to a stiffness driven approach, this also dictates the geometry of the box beams.

The box beam selected for this application has a ١٥٦x١٥٦ mm cross-section and a wall thickness of ١٣
mm. The overall bridge dimensions are shown in Figure ٤.

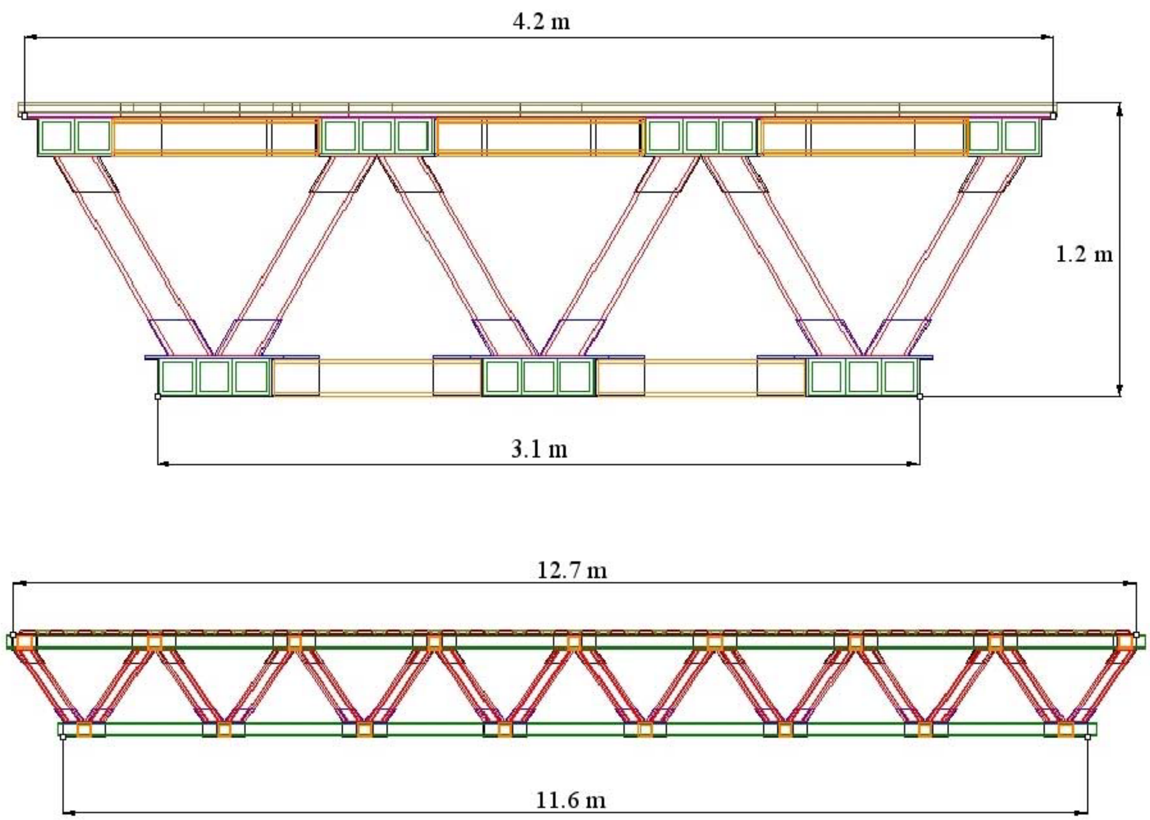


Figure ٤: The overall dimensions of the bridge

Materials and testing

The materials used for the pultrusion process, is S-Glass in roving form and in the form of plain weave fabric for the reinforcement and vinylester for the matrix material. This combination has been proven successful in many applications since it provides good manufacturing characteristics, good mechanical properties and excellent endurance to environmental wear, at a reasonable cost. The majority of the reinforcement content is in roving form and it was dictated by the need of maximising the bending stiffness of the beams. The presence of [±٤٥] plain weave fabric is necessary in order to secure the transfer of the load from the flanges through the webs of the box beams. The joints were manufactured out of steel, since their size and their complicated shape make the use of composite materials prohibitive. This is because the manufacturing processes required to produce composite components of such size and shape are not yet widely available. The increased weight of the metal parts doesn't encumber the structure considerably, as will be shown in the analysis section of this paper.

The material selection and the choice of properties used in the FEM analysis were based on a series of extensive mechanical tests. These can be categorised in coupon tests, beam tests, and tests on real scale assemblies. The coupon tests consisted of tension, compression, shear and bending tests. The results of these tests for the various material configurations are presented in Table ١. These material configurations refer to different production parameters (e.g. type of reinforcement, process-mould temperature, production speed, etc.).

Tensile Tests			
Material	**Modulus of Elasticity (GPa)**	**Tensile strength(MPa)**	**Poisson ratio**

١	٣١.٥	٥٣٠	٠.٢٦
٢	٣٠.٨	٥٣٠	٠.٢٩
٣	٢٩.٥	٥٨٠	٠.٣٣
٤*	٣٤.٧	٥٧٠	٠.٣٣
٥	٣٣	٤٦٥	٠.٢٩
٦	٢٩	٤٧٠	٠.٢٨

Compression Tests		
Material	**Modulus of Elasticity (GPa)**	**Tensile strength(MPa)**
١	٣٦.٥	٢٥٦
٢	٣٥.٥	٢٦١
٣	٣٥	٢٤٩
٤*	٣٨	٢٥٨
٥	٣٦	٢٥٤
٦	٣٤	٢٤٦

Three point bending tests		
Material	**Flexural modulus (GPa)**	**Flexural Strength (MPa)**
١	١٥.٣	٢٦٧
٢	١٥.٢	٢٦٤
٣	١٦.٧	٢٦٦
٤*	١٨	٢٩٦
٥	١٥.٢	٢٧٣
٦	١٧.٤	٢٨١

Table ١: Experimental results for the pultrusion materials

The box beams made for the bridge were also subjected to a series of tests, in order to ensure a consistent quality of the manufacturing process and to finalise the material properties for the modelling procedures. From the results obtained from the coupon tests the following properties were derived and applied in the analysis models.

Property	**Value**
Modulus of Elasticity **E**١	**٢٥ GPa**
Modulus of Elasticity E٢	**٦ GPa**
Tensile Strength	٥٠٠ MPa
Compressive Strength	٢٥٠ MPa
Shear Modulus	٢ (GPa)
Shear Strength	٢٥ (MPa)
Poisson ratio	٠.٣

Table ٢: Selected properties for material modelling

The above properties were verified by the beam tests.

A series of full-scale tests of sub assemblies of the bridge shown in Figure ٥ have been planned to carry out prior the construction of the bridge. These tests are aimed to verify the structural-numerical analysis and the material properties.

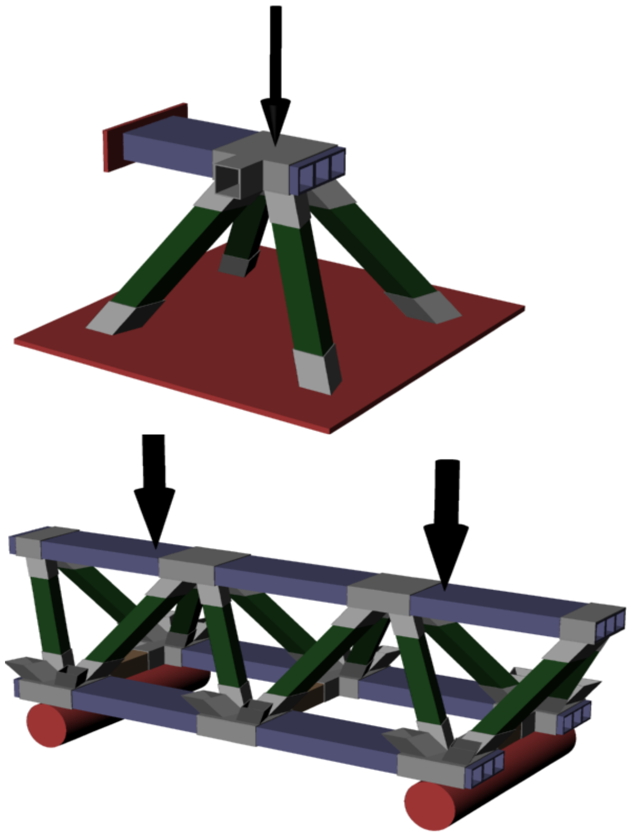


Figure ٥: Schematics of the real scale subassembly tests

Numerical analysis

The structural analysis of the bridge was carried out in two steps, an overall analysis of the bridge and a detailed analysis focused on the assembly between the joints and the truss member beams. The first step was conducted using the civil engineering FEM code Sofistik. The structure was modelled with beam elements and appropriate displacement conditions were imposed on their connection points in order to simulate the node behaviour. The analysis was conducted for two cases of the load's position on the bridge i.e. for the load applied at mid-span and over the support. This analysis step yielded the displacement profile and the maximum forces and stresses developed on the beams. The results indicated, as expected, that the stresses on the beams are far from critical and that the overall design is stiffness driven. The truss was also analysed neglecting the weight of the metal joint and the resulting displacement was about ٠.٩ mm less than the true displacement. This shows that the weight of the metal parts being concentrated at the nodes of the truss has no significant effect on the performance of the structure. In fact a ٥٠% increase of the dead load due to the weight of the joints, results to a less than ٧% increase of the maximum displacement (Table ٣).

Loading	**Maximum displacement neglecting the joints' weight**	**Maximum displacement including the joints' weight**
Dead load	١.٢ mm	٢.٠٨ mm
Dead + live load	١٢.١٧ mm <L/٨٠٠=١٢٠٠٠/٨٠٠=١٥ mm	١٣.٠٦ mm <L/٨٠٠=١٢٠٠٠/٨٠٠=١٥ mm

Table ٣: Maximum displacement of the bridge

The second step was the analysis of the joints under the loads obtained from the first step. The MSCNastran and the LS-NIKE٣D FEM codes were used for this part of the analysis. First of all, the critical

joints were identified based on the internal forces developed on the beams that run through them. After
that, detailed models of the various types of joints that included the assembled beams were developed. These models were subjected to the loads developed on the beams. The results show that a thickness of ٨mm for the steel sheet results to the desired load bearing capacity of the component. In the following, some selective results of the analysis on a central joint node are presented in Fig ٦-١٠.

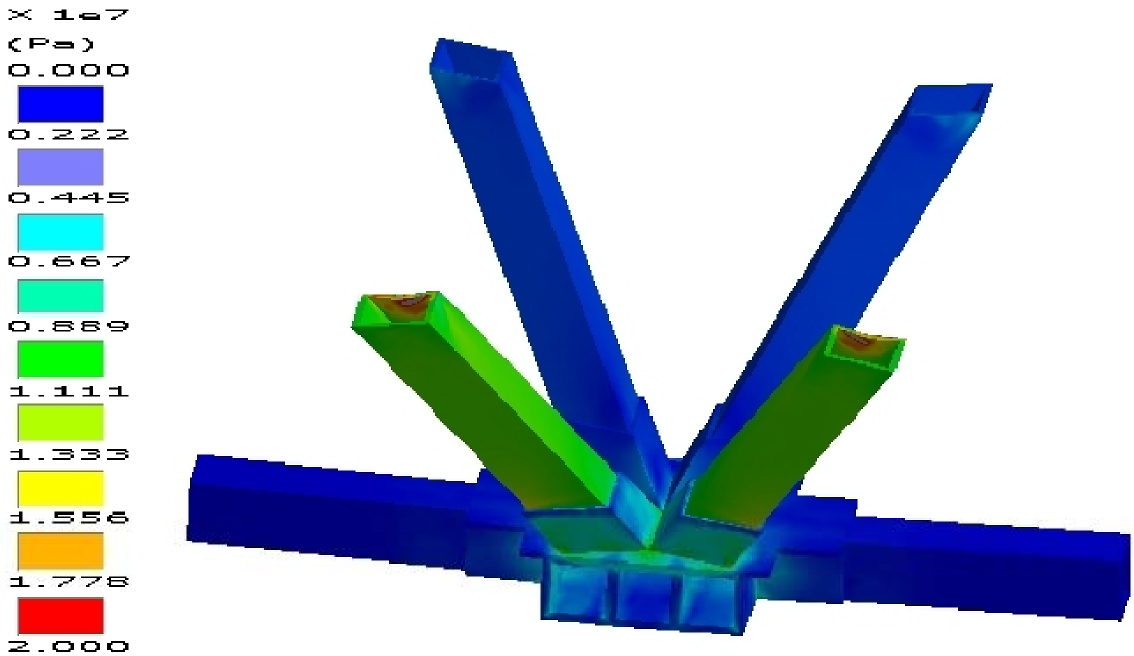


Figure ٦: Equivalent stress contours for the joint assembly model (full view)

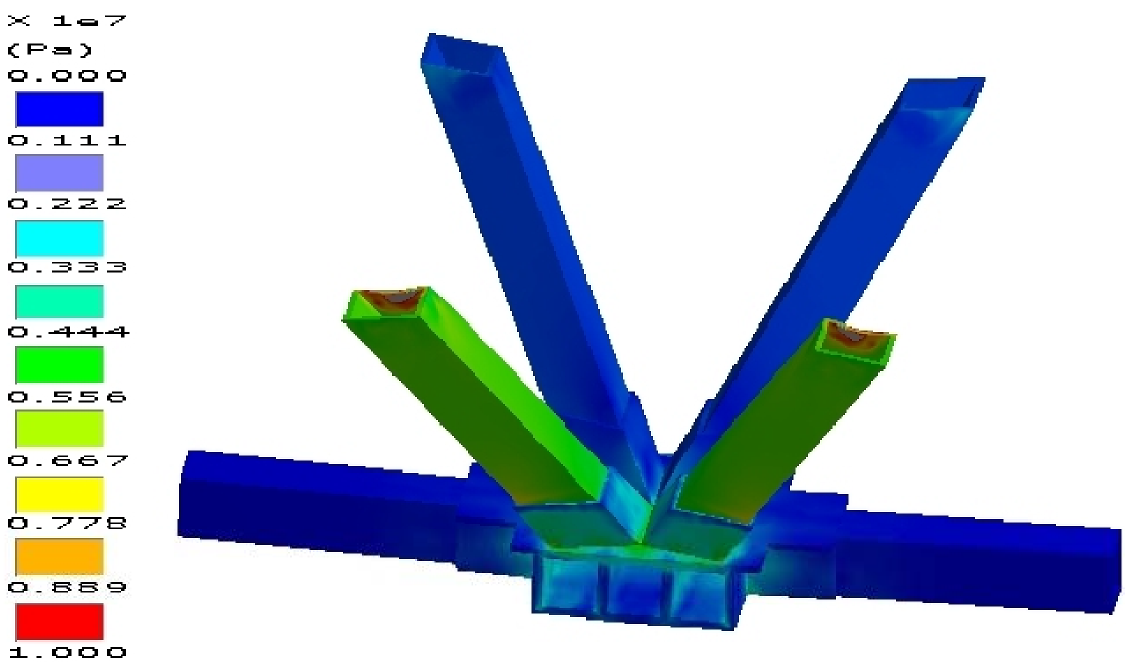


Figure ٧: Maximum shear stress contours for the joint assembly model (full view)

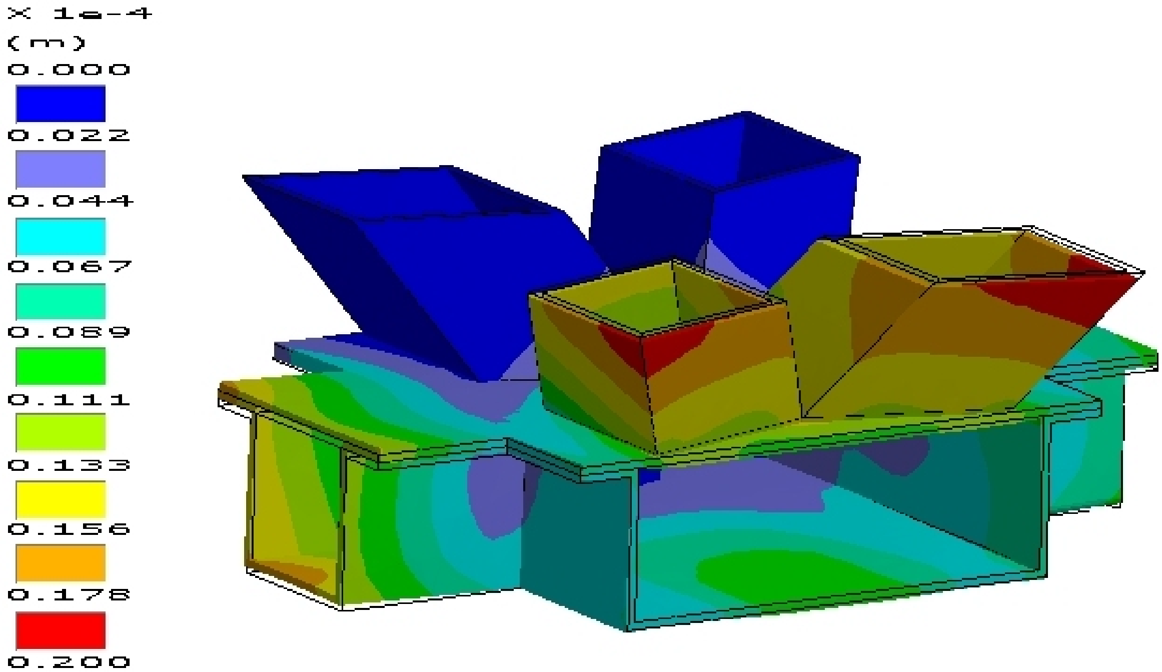


Figure ٨. Displacement contours for the for the joint assembly model (detail)

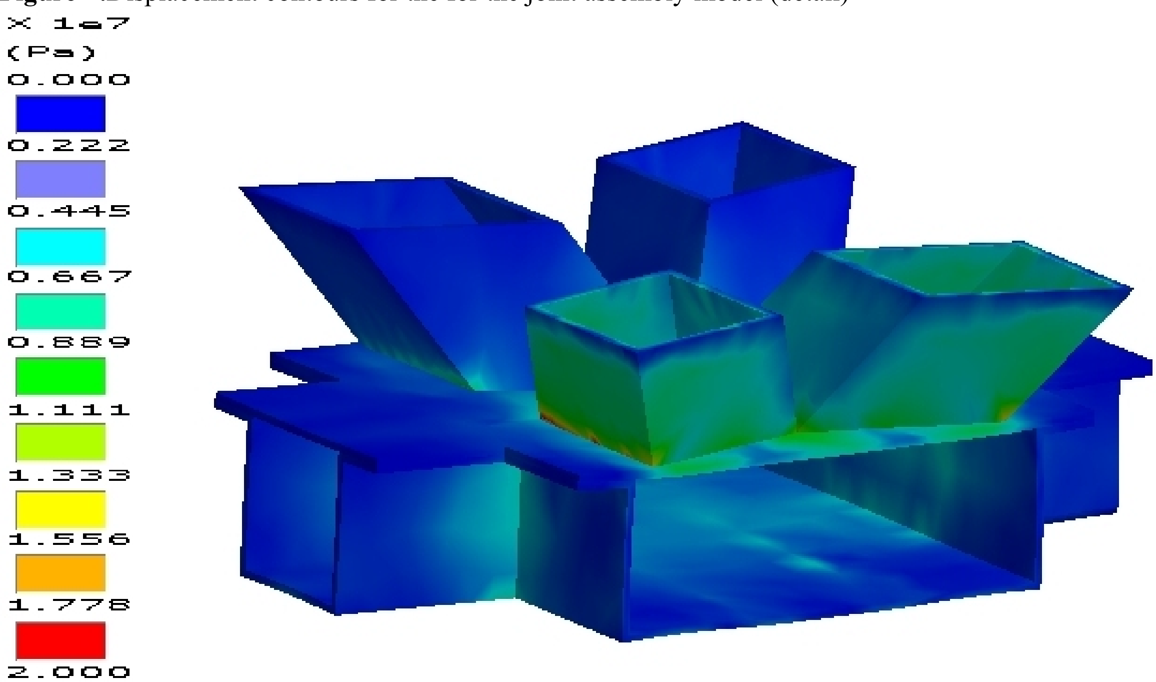


Figure ٩. Equivalent stress contours for the joint assembly model (detail)

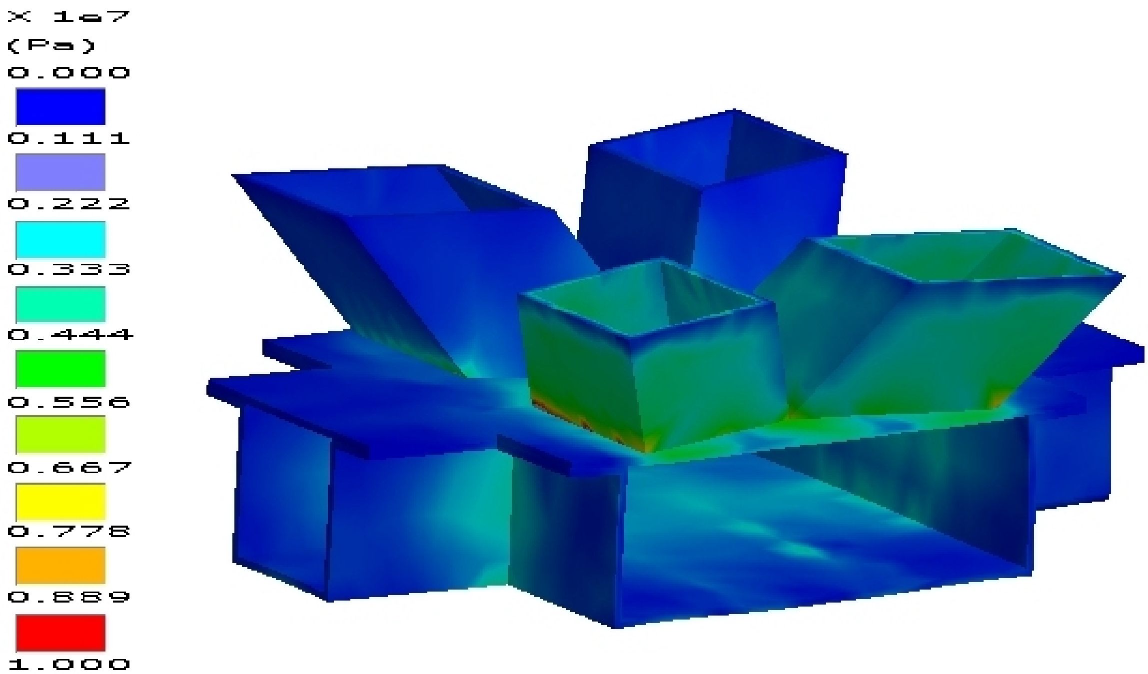


Figure ١٠: Maximum shear stress contours for the joint assembly model (detail)

The deck beams were also analysed in details for their behaviour under the direct loading of the vehicle wheels.

Two models were developed, one having the beam under flexural loading conditions and one under crushing conditions. These models are presented in Figures ١١,١٢. On both models the wheel loads specified by the DIN standard were used, increased by a safety factor of ٢. The results in terms of both

stress and deformation are shown in Figure ١٣

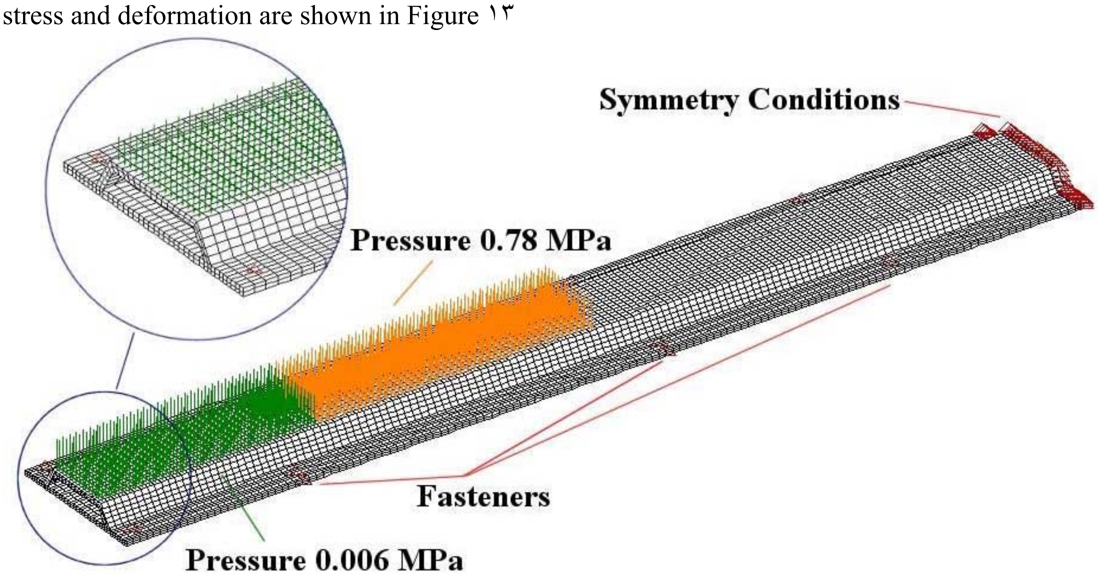


Figure ١١: Analysis model for the deck beam under bending conditions

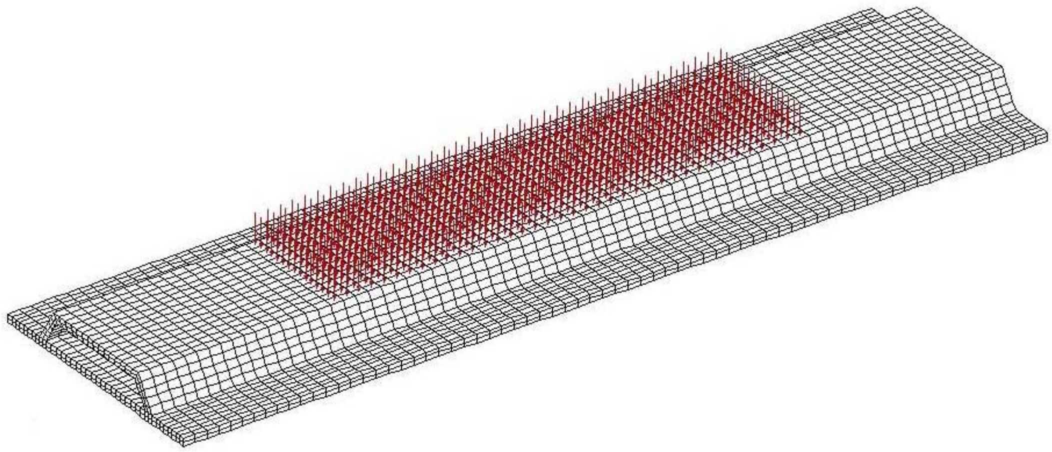
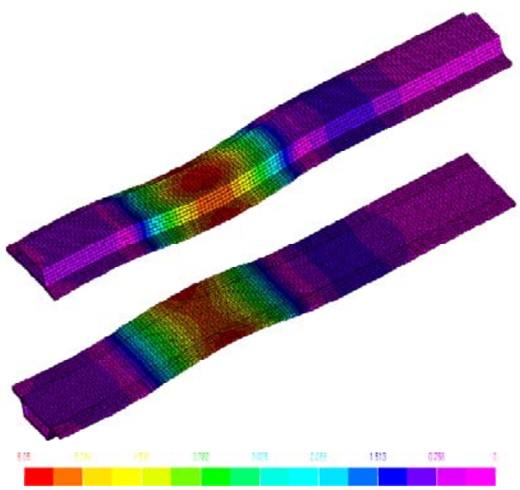
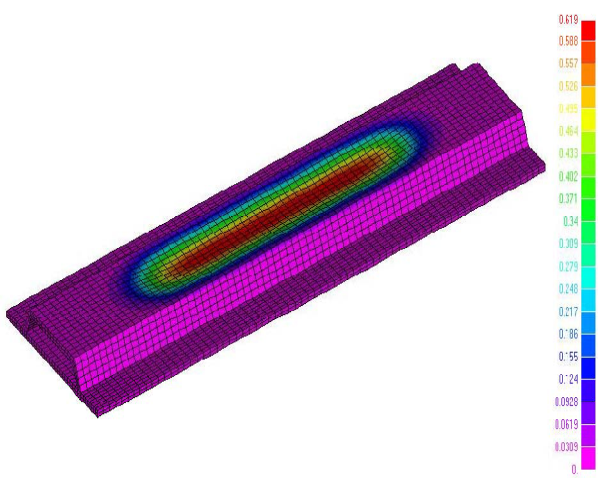


Figure ١٢: Analysis model for the deck beam under compressive crushing load.





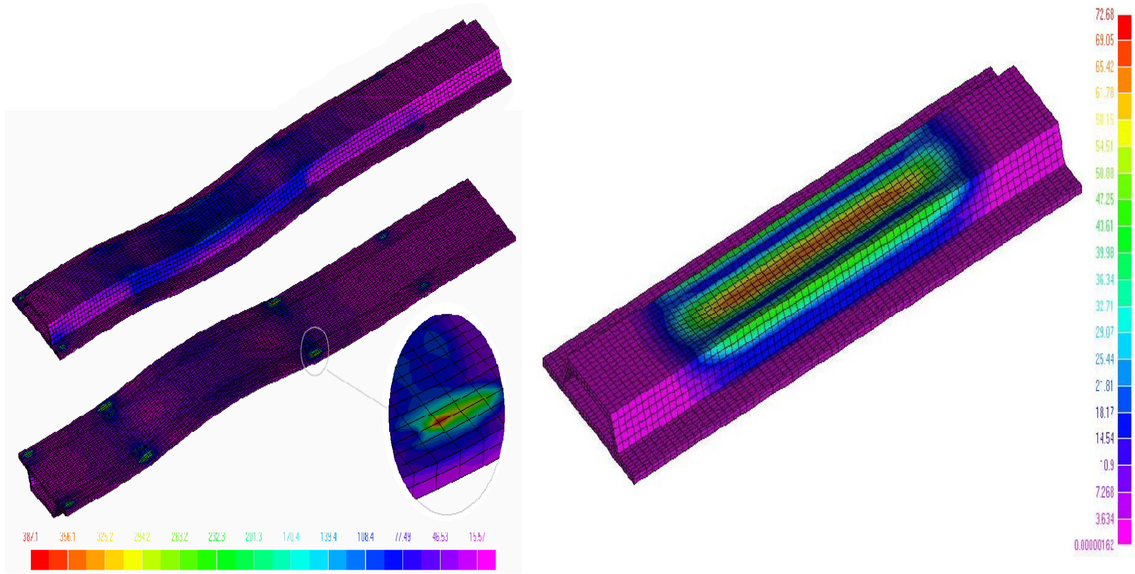


Figure ۱۳: Translation and Von-Misses stress contours for the deck beam under a) bending and b) compressive loading

The FRP was modelled as ۲D orthotropic material since it is clear that pure unidirectionally reinforced composites exhibit such behaviour. The values of stiffness and limit stress for each direction of the material were the ones obtained by the material characterisation tests.

Discussion-Conclusions

The present study describes the application of composites made using the pultrusion process for the design and construction of a highway bridge. The design was based on a truss concept, thus utilising the exceptional strength and stiffness of FRP beams under the loads applied on truss members. Unlike other concepts for the application of composites in civil engineering, the main structural members of the truss are made using an automated, large-scale production process. Moreover, the size of the required components and the materials selected, render the production within the efficiency of medium capacitypultrusion equipment. The main disadvantage of the proposed application, regarding its novelty, is the usage of metal joints that act as the nodes of the truss. However, metal construction was the only cost effective mean to produce such components, whose design made possible to utilise massively produced composites for the bridge structure. The alternative of using composites for those large and complex parts would have made the whole concept self-contradictory, due to the exaggerated cost.

The analysis results have shown that the structure can carry the specified loads with safety.

Future work will emphasise on establishing the modular character of the proposed concept by implementing the same design principles and procedures to various bridge applications in respect to their size and suspension methods. The analysis conducted so far, has shown that the structural efficiency of the model bridge is well within the design requirements. The model bridge will be subjected to a number of instrumented tests that will continue on for several years, in order to examine its structural integrity and to locate possible wear-prone regions.

Acknowledgment

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