A Rapidly Deployable Bridge System

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ABSTRACT

Rapidly deployable mobile bridges are of direct relevance to military and civilian agencies. The US Army uses such bridges in a broad range of applications including assault, tactical, and general communication. Civilian use extends from temporary infrastructure improvements during natural disasters to planned situations that are equally critical. This paper describes a modular bridge system developed primarily for use in assault scenarios where rapid deployment is vital, but this design concept is also relevant in civil applications. The robust metallic design of the bridge is based on an aluminum trussed arch reinforced by steel cables. The segmental form of the structure allows it to be folded into a compact package for transportation in a standard 40 ft container, which facilitates shipping by road, rail, sea, or air (C-130 transport aircraft). The bridge segments also facilitate adaptation of the bridge to different spans ranging from 8m to 32m. The load rating for these spans varies between 100T and 40T respectively. The preferred deployment approach for the assault configuration uses a scissor method in conjunction with a winching mechanism mounted on an auxiliary bridge guide. Compared to more conventional techniques, this method reduces the demands on the bridge launcher. The complete system provides an integrated solution to cover a broad spectrum of bridging applications. Extensive computer analysis was used to refine and optimize the components in the bridge. Structural testing of components during the design stage also helped guide the design process, and operational and load testing of a prototype system using strain gauging confirmed the integrity of the final design.

INTRODUCTION

Military Bridges are classified by the mission that they serve, of which there are three types. The first mission type is the Assault mission. An example of a bridge used for an Assault mission is shown in Figure 1. These bridges are characterized by their high mobility and survivability, due to their need to support combat forces in hostile environments. Bridges deployed in assault missions are typically transported by a tank, launched and retrieved over a gap in a matter of minutes, and used multiple times in a matter of minutes.

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Figure 1: Existing Bridges for different missions – Assault (top left), Tactical (top right) and Line of Communication (bottom)

The second type of bridging mission is the Tactical mission - also shown in Figure 1. Bridges deployed under these missions typically require more resources, site preparation, and time than the assault bridge. The Tactical Bridge typically replaces the assault bridge, once control of an area is obtained, and provides a semi-permanent means to quickly cross gaps. Tactical Bridges are designed to carry higher volumes of wheeled and tracked traffic and be left in place for longer periods of time than Assault Bridges.

The third type of bridging mission is termed Line of Communication is also shown in Figure 1. This mission begins once full control of an area is obtained. This type of bridge requires the longest amount of time and greatest number of resources to deploy. However, they provide the military with a permanent structure capable of carrying high volumes of military and civilian traffic, and ensure that the flow of supplies, equipment and personnel is uninterrupted.

The military currently has many different bridging systems which fall under these three missions. None of these systems are interoperable with each other from a structural standpoint, nor are they deployable using a single platform. This results in a large logistical and operational footprint that needs to be managed on a daily basis. The need to reduce this footprint resulted in the initiation of a program to develop a system which can be reconfigured for use in multiple Military Bridging missions. This paper describes one potential solution to this requirement.

BRIDGE SYSTEM DESIGN REQUIREMENTS

The requirements for the bridge system described in this paper were assembled into a comprehensive specification-type document that can only be summarized here. Of particular interest are the loads that the bridge must accommodate as well as some other parameters - including span - which are listed in Table 1.

Table 1: Design Requirements

Bridge application	Assault (Primary)	Tactical and Line of Communication (Secondary)
Span	8m – 18m (Primary)	Up to 32m (Secondary)
Vehicle Load	40T (Primary)	50T-60T (Secondary)
Impact Factor	1.15 Primary - for speed < 15mph)	1.4 for speeds up to 25mph (Secondary)
Factors of Safety	1.5	With respect to Ultimate Strength
	1.33	With respect to Yield Strength
	1.5	With respect to Buckling Strength
Maximum slope	1:6	
Storage/Transportation Package	480in x 105in x 102in and <36,000lb	Requirement based on C130 transportation

Of the requirements listed in the table the ones denoted by “primary” are fixed i.e. non-negotiable, whereas the ones denoted as “secondary” provide a competitive advantage over existing solutions.

BRIDGE DESIGN

In the development of a bridge concept that meets the design requirements it became clear that the upper end of the span range coupled to the maximum transportation package dimension leads to the need for a folding - or otherwise articulated - deck system. This in turn requires an efficient hinge system which became a central feature of the concept proposed herein.

A prototype bridge based on the developed design concept is shown in Figure 2. This version of the bridge system is designed for Military Load Classification 30 (MLC30) vehicles crossing a 12m gap.

Figure 2. Prototype bridge for MLC30/12m assault missions.

Some of the key features that evolved in the design development and are apparent in Figure 2 and 3 include:

- Tied-arch structural system
- Laminated (or interleaved) modular construction
- Hinges for folding
- Treadway design with no deck cross-members
- Modular all-aluminum construction
- Custom extrusion chords
- ‘Riv-bonded’ joints using bolts and high strength adhesive within modules

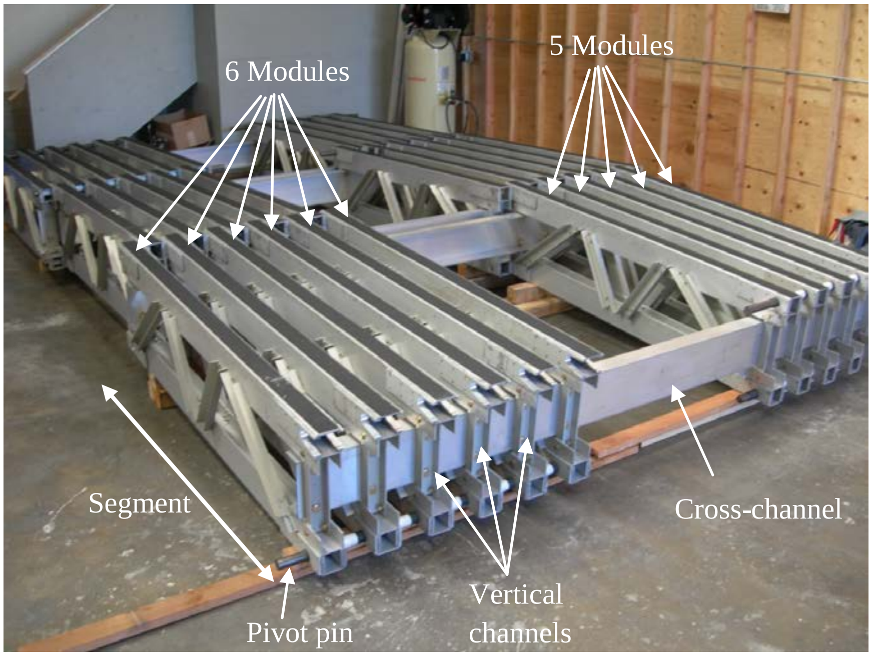


Figure 3. Half-bridge assembly of three segments, each consisting of eleven modules.

The segment employed for the prototype bridge system consists of eleven modules arranged in a 6/5 configuration. A segment weighs approximately 1,200lb including all modules, channels, and hinge pins. The resulting bridge capacity and geometry is consistent with an MLC30 load and vehicle width. Accommodation of heavier vehicles would require an increased number of the same modules. The module design was initially developed and optimized for an MLC50 load in a 20m span but is only slightly sub-optimal with respect to weight when used in an MLC30/12m configuration. The MLC50/20m system uses 17 modules in a 9/8 configuration.

The connection of the modules to each other is by means of the vertical channels at the ends of the modules and the large cross-channels that span the width of the bridge. These Al 6061-T6 cross-channels can be extended as needed to accommodate wider/stronger segment configurations by splicing additional short lengths to the outer ends of these members. Alternatively, the channels could be fabricated to the required length, for which three different versions would be required based on the geometries anticipated in Table 1. None of the inter-module connections use adhesives as this would detract from the inherent modularity of the bridge system. Similarly, none of the inter-segment connections described in the next section use an adhesive, for the same reasons.

There are two types of segments used in a complete bridge with the subtle difference between them apparent in the computer rendering of Figure 4. This figure also shows another important feature of the bridge design. It is apparent that the two central segments are not parallel, but have an offset angle of 4^o. This change in slope ensures the arch-shape that is critical to the bridge structural behavior. The change in slope is present in the central two segments—regardless of bridge span. Thus the initial slope of 6^o changes to 2^o, then to -2^o and finally to -6^o as the bridge is traversed. This change in angle is achieved by slight offset of the pin holes in the bearing plates for the modules in the two central segments.

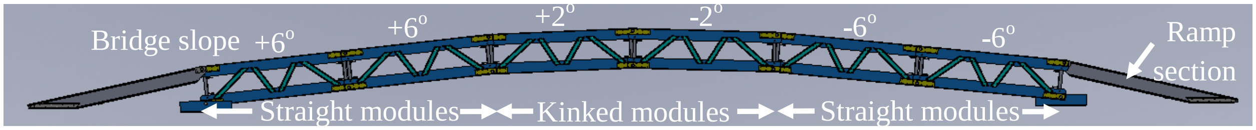


Figure 4. Change in deck slope from module to module is accommodated by slight offsets from a rectangular pattern of pivot points in the kinked modules.

Another unique characteristic of the central segments that requires some explanation is apparent in Figure 5. The segments that straddle the midspan have slotted holes to facilitate the folding of the bridge at half-length as is required for a scissor method of deployment. Modules in one of the two segments that meet at the middle of the bridge utilize the slotted holes while the corresponding modules on the other side of the centerline capture the hinge pin in a conventional way. This arrangement is also shown in Figure 5. Note that slotted holes in the modules exist only at midspan for typical bridge configurations.

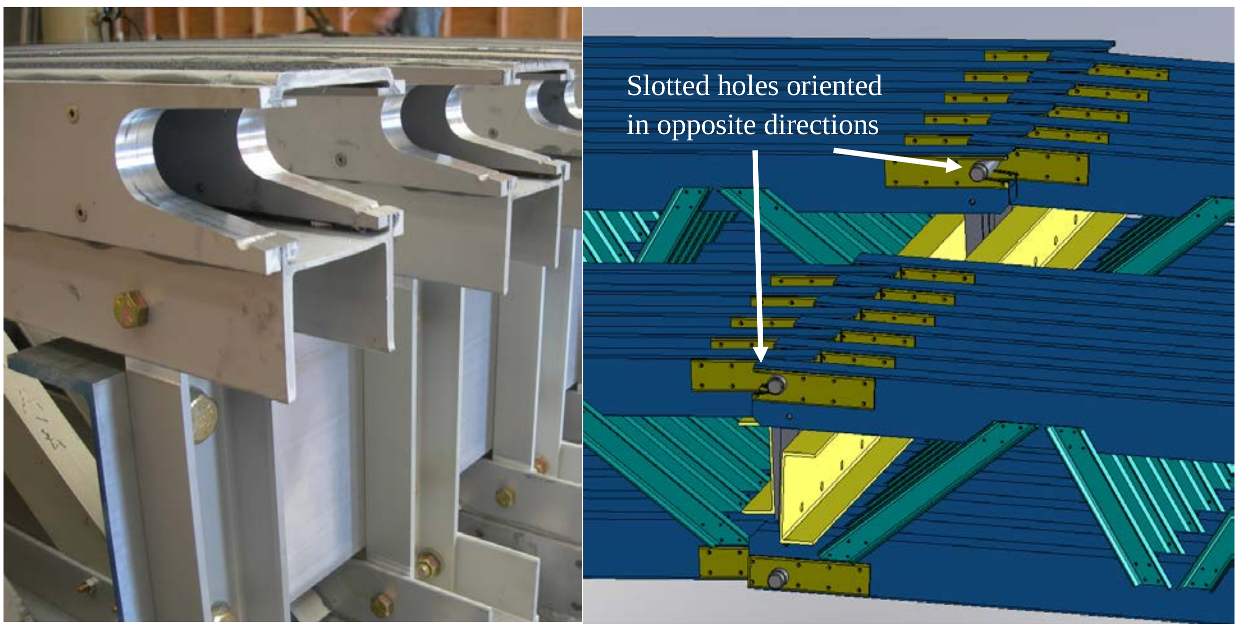


Figure 5. Slotted holes are used for the upper hinge-pins for one side of the centrally-located segments to facilitate scissor operation of the bridge.

The bridge description provided in this section emphasizes the important structural and manufacturing features of the bridge system. The following sections provide analytical and test data to confirm the superior structural performance of this system when subjected to the loading environment described in the design specification.

ANALYTICAL APPROACH AND RESULTS

During the design of the bridge system, extensive finite element analyses were performed to predict its strength and stiffness. This work, which was done twice—first for the MLC50/20m and then MLC30/12m configurations—is the subject of the following sections. The strength testing took place later in the program and generally confirmed the validity of these results.

The modeling approach used for the bridge analysis consists of a two-prong procedure. A beam model of the entire bridge was constructed, subjected to design loads, and the most highly stressed module identified. A detailed shell model of this module was then subjected to interface forces extracted from the complete-bridge analysis. This second detailed analysis allowed factors of safety with respect to yield and buckling be evaluated. A variation of this two-step procedure was sometimes used in which the shell model was spliced into the complete bridge beam model. This latter approach proved to be more time-efficient in situations where the peak stresses were always encountered in the same particular module in the bridge structure.

The overall beam model for the MLC50/20m configuration is shown in Figure 6 along with the detailed shell model of one module.

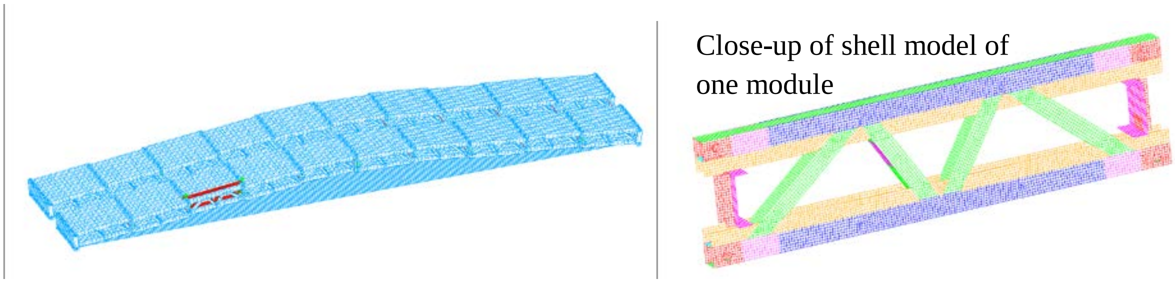
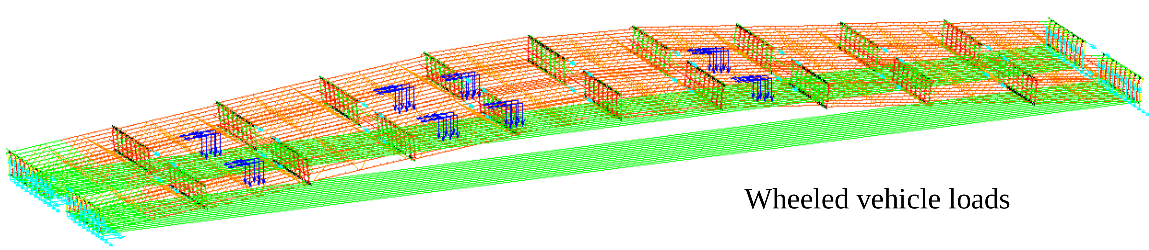


Figure 6. Complete model of entire bridge with all beam elements shown in blue and the spliced-in detailed module shell model in red.

The two types of primary loading, shown in Figure 7, represent wheeled and tracked vehicles as specified in the governing requirements document.



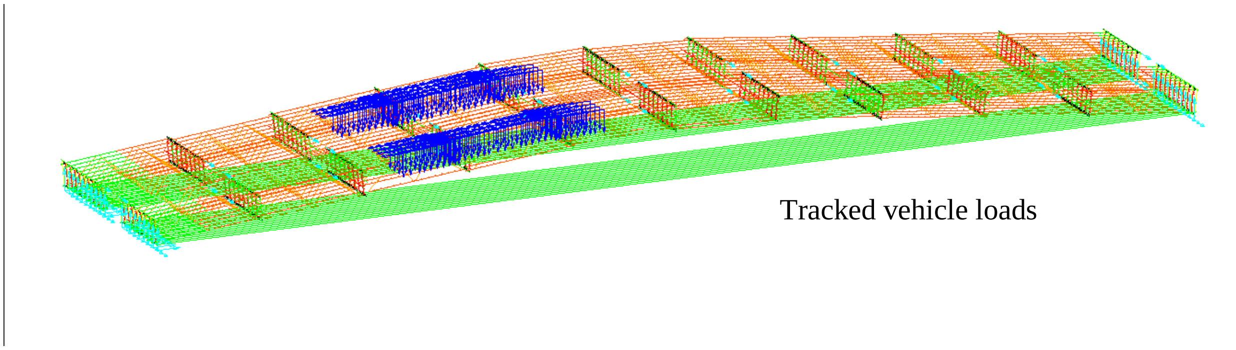


Figure 7. Blue arrows indicate the location of the tire (upper) and track (lower) loads applied to the MLC50/20m model for typical load cases.

The loads shown have vertical and longitudinal components to account for gravity (including impact) and braking effects. The specified impact factor of 1.35 is typically used in the analyses reported herein. A braking factor of 0.65 is used throughout in accordance with Reference 1. A total of 15 load cases were analyzed for each of the tracked and wheeled configurations to represent different locations of the vehicle on the bridge—longitudinal and lateral. In a typical load case a vertical load of 1.33 x (vehicle weight) is combined with a longitudinal load of 0.65 x (vehicle weight). Only one vehicle is present on the bridge in any load case.

The materials used in the bridge and their associated mechanical properties are listed in Table 2.

Table 2. Material Properties

Material	Components	Modulus	Yield Strength	Ultimate Strength	Bearing Strength	Allowable Stress[1]
Al 6061-T6	All standard extrusions	10×10^6 psi	35 ksi (2)	38 ksi (2)	54 ksi (2)	25.3 ksi
Al 2024-T8511	Chords	10×10^6 psi	63.8 ksi (3)	71.2 ksi (3)	82 ksi (2)	47.5 ksi
17-4PH SS H1150	Hinge Pins	30×10^6 psi (2)	143 ksi (4)	157 ksi (4)	-	104.7 ksi
SS T316	Cables	30×10^6 psi	-	116 ksi	-	77.3 ksi

The stress results for the bridge analysis are presented only for two the MLC50/20m configurations because this drives the design. The stresses in the aluminum members are shown

[1] Allowable stress is calculated as the lower of the two values: (Ultimate Strength)/1.5 or (Yield Strength)/1.33 in accordance with Reference 1.

in Figure 8 for the most severe tracked vehicle load case. In this case the tank, which straddles bridge segments 3 and 4, is offset as far to the right as possible when the bridge is traversed from left to right. The highest stress calculated for this case is 34.1ksi, occurring in the loaded top chord directly under the tank, and has sufficient margin compared to the 47.5ksi allowable stress for that material. The highest stress in any of the 6061-T6 sections (all module members other than chords) is 19.8ksi, occurring in a web channel in the same module as the highest-stressed chord.

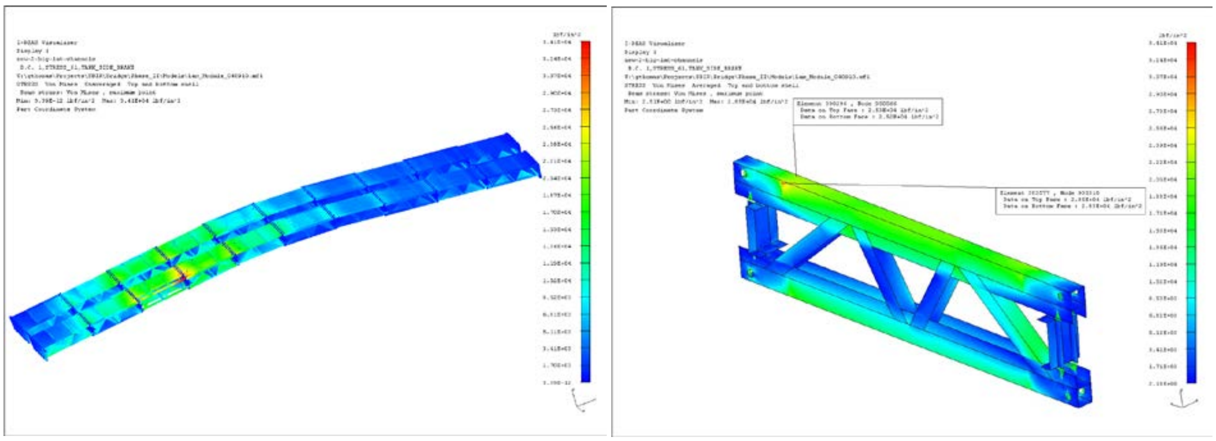


Figure 8. Stresses in aluminum beams for the most severe load case analyzed - MLC50 tank located close to the high stress area but offset as far as possible in the +ve Z (lateral) direction. The highest stress anywhere in the aluminum is 34.1 ksi in the top chord under the tank treads.

An important observation about the stresses in the top chord at the bearing plates is that the stresses close to the pin holes as predicted by the shell model are quite modest. A contact stress analysis had previously been undertaken to establish the bearing plate thicknesses. This more detailed analysis provides a more reliable estimate of the stresses at the pin/bearing plate interface.

The stress distribution in the aluminum components for the most severe wheeled load case (Figure 9) follows a similar distribution to that shown for the tracked vehicle load case in Figure 8. The stresses are slightly lower in this case as is true for all other wheeled vehicle load cases.

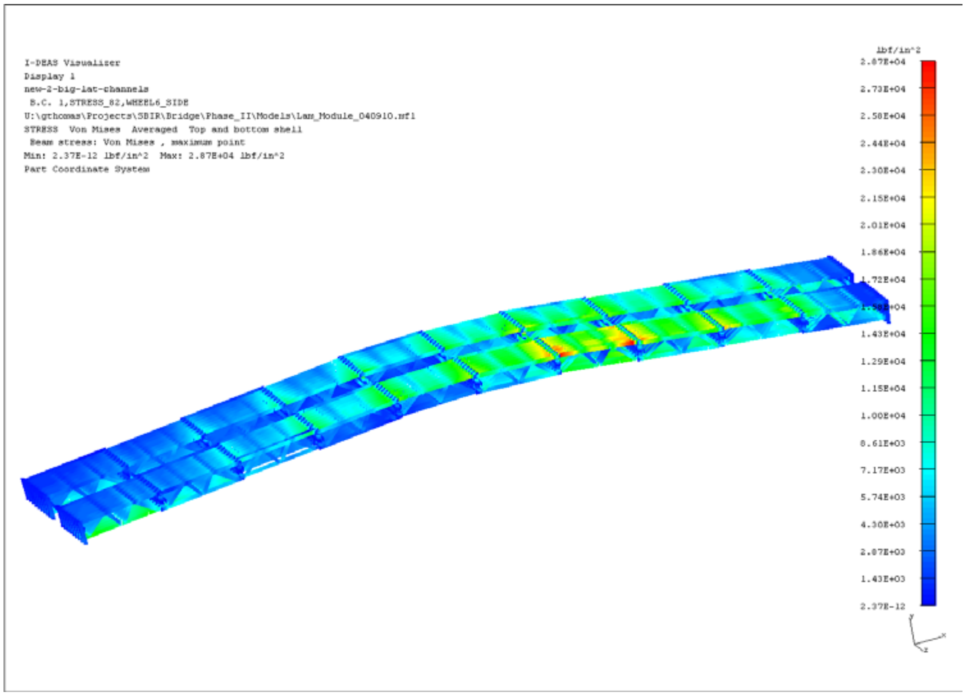


Figure 9. Stresses in aluminum members for the most severe MLC50 wheeled vehicle load case. The vehicle is offset in the +ve Z (lateral) direction as far as is possible for the treadway design geometry. The peak stress is 28.7ksi for this case.

Elastic buckling is another failure mechanism that needs to be checked at two levels—as a complete bridge and locally within each module. Details of the buckling analyses that were undertaken are beyond the scope of this paper, but the resulting buckling load factors are approximately 4.0 for local and global modes compared to the required factor of 2.0.

TEST PROGRAM, RESULTS AND COMPARISON WITH ANALYSIS

Testing was undertaken in this bridge development program at different levels from the component level to the complete bridge. Joint tests and module tests conducted early in the program provided data to facilitate systematic progress in the evolution of the design. The primary objective of the complete bridge testing was to confirm the acceptable structural performance in the presence of specified design loads. Test measurements would also provide added confidence in the analytical stress predictions.

The test cases that were included in the program included static tracked-vehicle loads applied at symmetric and asymmetric positions both longitudinally and laterally to make four cases in total. The maximum load used in any load case was 84kip which, even though it is significantly greater than the 60kip weight of an MLC30 tank, is lower than the 92kips required in an overload qualification test.

The instrumentation used in the test consisted of 16 strain gauges on the top and bottom chords of highly stressed modules, 2 strain gauges in the upper central pivot pin, vertical and lateral displacement transducers at mid-span and accelerometers on the tie cables to facilitate natural frequency and hence cable tension measurements.

The results for all 34 channels of strain and associated displacement and acceleration data for all load cases are far too extensive to present in this paper but some representative and important data are presented herein. The strains in the four gauges of a mid-span interior module are shown in Figure 10, along with the analytical prediction in each case.

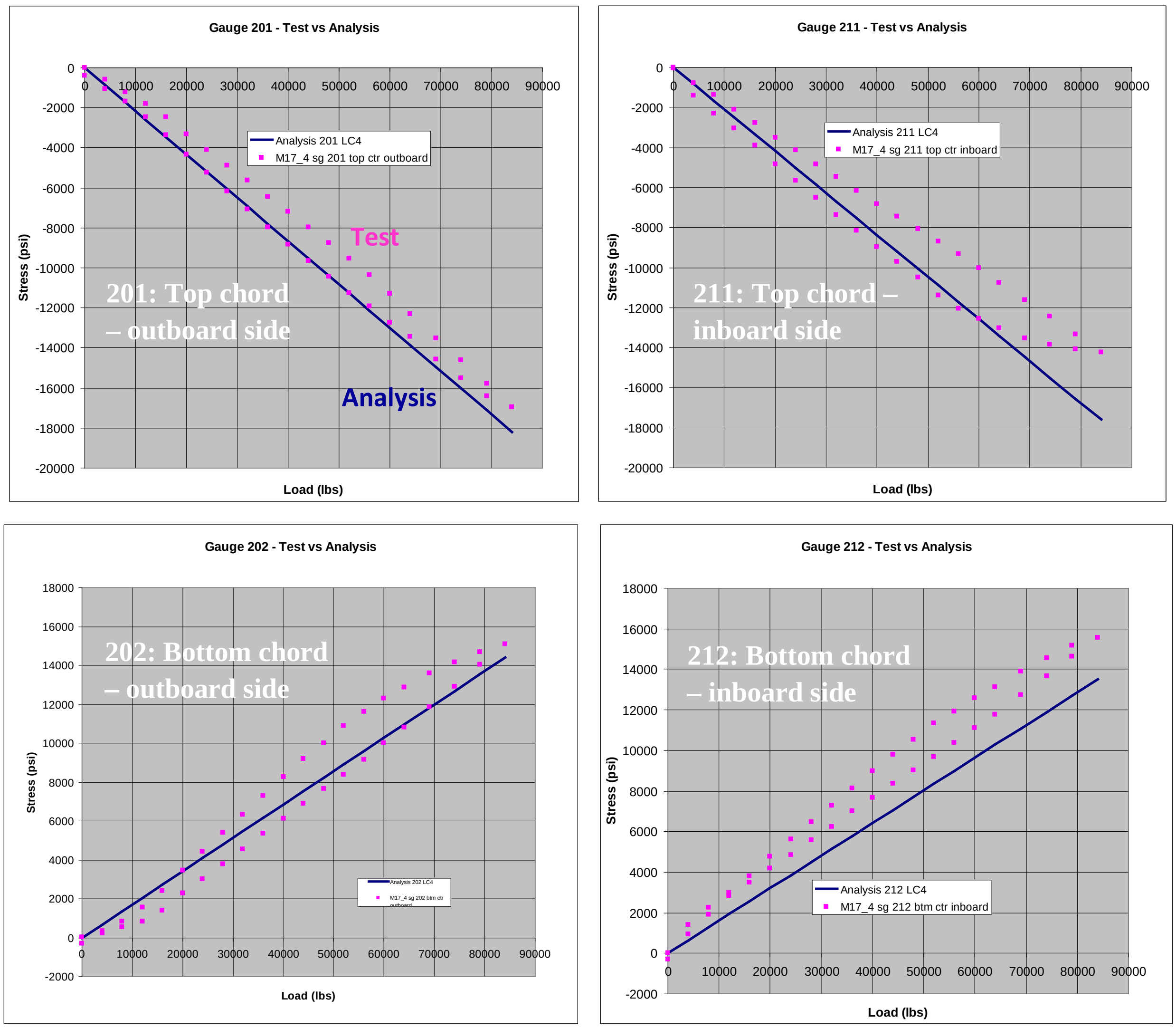


Figure 10. Comparison of test and analysis results for chord gauges with centrally located but laterally offset tracked vehicle load.

The agreement between analysis prediction and test measurement is generally quite good, although there is a tendency for the model to over-predict top chord stresses but under-predict bottom chord stresses. This deficiency is consistent across all gages. It is believed that the tie-cables are not as effective as implied by the model resulting in less compression in the chords than expected. Thus the top chord compressive stresses are less than expected whereas the bottom chord being in tension receives less beneficial stress cancelling than expected. It is believed that had a cable tensioning system been incorporated into the design this type of discrepancy could be reduced. Future versions of the bridge design will probably include turnbuckles for this purpose when the use of tie cables is deemed beneficial and cost effective.

CONCLUSIONS

A design concept has been developed for a deployable bridge suitable for assault applications. The bridge system utilizes modular construction extensively to facilitate configuring hardware to satisfy a broad range of load and span requirements as the need arises. Extensive finite element analysis has shown that the bridge system can accommodate vehicle ratings MLC20 to MLC100 for spans varying from 32m down to 8m. The design configuration for which the system was optimized is MLC50 with a 20m span in accordance with the design specification.

The structural concept used for the bridge system is an efficient tied arch in which aluminum trusses are laminated together to achieve high strength as well as facilitating the folding of the bridge into a compact package for transportation and storage. Readily available 6061-T6 alloy is used for many of the bridge components with a higher strength 2024-T8511 alloy being used for the more highly stressed truss top and bottom chords and the associated bearing plates that interface with the stainless steel hinge pins. Mechanical fasteners and a high–strength adhesive are used at all the permanent joints in order to achieve the full strength of the complete structure while avoiding premature joint failures.

A prototype version of the bridge system was built and tested. This version corresponds to a 12m span to accommodate gap crossing by an MLC30 vehicle. This bridge was tested with a vertical load of 84kip which is much greater than the specified operational load of 69kip and only slightly lower than the 92kip load that would be used in an overload test. Given that the maximum stress in the structure was measured in the test to be significantly less than the yield strength, there is a high level of confidence that the overload and even the ultimate load (104kip) can be handled safely by the bridge.

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