RAPIDLY DEPLOYABLE, PORTABLE, GFRP VEHICLE BRIDGE DEVELOPMENT PROJECT

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ABSTRACT

To investigate the appropriateness of lightweight, inexpensive, short span bridges for the Canadian Forces' new fleet of wheeled vehicles, a 4.8 m span prototype tapered box-beam was constructed using commercially available GFRP pultruded sections. The low modulus of elasticity in tension and compression were considered in the development of the structural concept presented. This paper reports on this development project to date with emphasis to the numerical modeling carried out to support the project. A 4.8m span representative structure of the proposed bridge was constructed in the laboratory and tested under a variety of static load conditions. These results are reported and compared to the numerical predictions derived from Finite Element Models (FEM) of the structure. The FEM analysis included both overall structural responses under static load as well as localized stress predictions in the areas of complex critical joints using a combination of 2D and 3D modelling techniques. The load-displacement behaviour of the tapered box-beam was closely predicted by both a simplified strength of materials calculation of the built-up cross section and a 3-D linear finite element analysis that included the diaphragms. At the maximum test loads, the displacements were acceptable, and the tests showed good transverse stiffness and good lateral stability. The low modulus of elasticity of the plates led to significant local deflections of the top plate between the diaphragms. Since these tests were conducted without the wearing surface grating, it is expected that subsequent tests with the grating will result in improved stability of the top plate.

1. INTRODUCTION

Since the late 1980's the Royal Military College of Canada has been involved in the testing of GFRP bridges of various configurations. These bridges, mostly of various truss configurations, including aramid and steel prestressing cables, have demonstrated their functionality under many service conditions [1, 2]. Service conditions examined have included: static, dynamic [3], cold temperature, fatigue [5] and sustained load. The goal of recent efforts has been to adapt lessons learned from early footbridge configurations to develop a useful short-span vehicle bridge.

The current needs of the Canadian Forces have focused this project more specifically to its evolving requirements in support of Pease Support Operations (PSO) mounted around the world. Traditionally, militaries have relied on their tracked vehicles to provide their cross-country mobility, both intrinsic to the vehicle and through alloy bridges launched from tank chassis. The current nature of operations has seen the Canadian Military evolve towards a more wheeled fleet, particularly when deployed on PSOs, which lacks the traditional mobility capability mentioned above. The current development project was undertaken to provide recommendations for structures constructed of commercially available pultruded FRP products that could be used as gap crossing structures using modular principles. These structures could be mounted on vehicles and erected with minimal support. The designed structures would fulfil a gap-crossing requirement between the vehicle's own mobility and traditional assault bridging. Critical to this concept was the requirements for the bridge to be light-weight, low-profile, modular, highly portable and thus rapidly deployable.

This paper reports on this development project to date with emphasis to the numerical modeling carried out to support the project. A 4.8m span representative structure of the proposed bridge was constructed in the laboratory and tested under a variety of static load conditions. These results are reported and compared to the numerical predictions derived from Finite Element Models (FEM) of the structure. The FEM analysis included both overall structural responses under static load as well as localized stress predictions in the areas of complex critical joints using a combination of 2D and 3D modelling techniques.

2. MATERIALS AND CONSTRUCTION

A 4.8 m span prototype tapered box-beam was constructed using commercially available GFRP pultruded sections and bonded connections throughout. The quasi-static behavior of the prototype box-beam was investigated in ambient laboratory conditions. Figure 1 shows a 3-dimensional model of a single track of the proposed bridge tested in the laboratory. Plate members have been shown as partially transparent to enhance internal detail visibility.

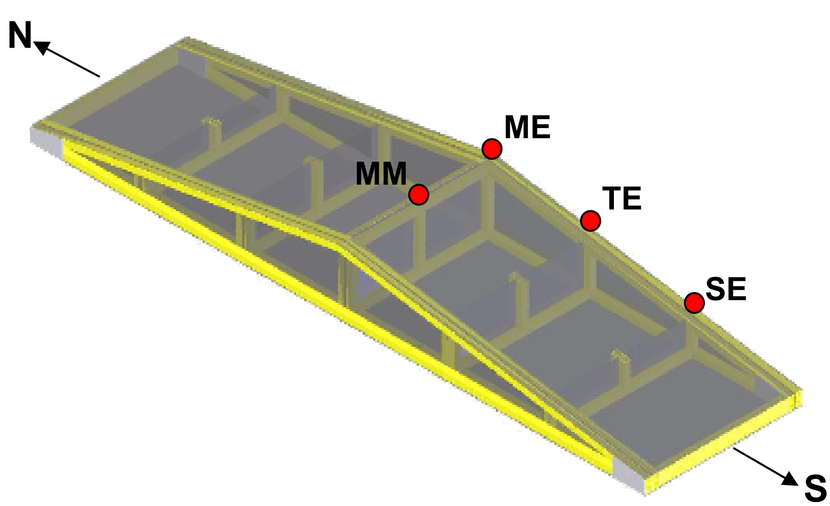

Figure 1 - 3D Model of 4.8m FRP Bridge (Plate members shown as transparent for internal clarity)

The structure consisting of a horizontal base plate, two triangular shape web plates, and an inclined ramp or top plate with a slope of 9.4°. The overall width of the box-beam is

1.2 m, and its length is 4.8 m. Without the wearing surface, the maximum height at mid-span is 0.5 m, and the minimum height at the ends is 0.102 mm. The full structure would consist of two tracks, lightly laced together with bolted GFRP sections.

The box-beam is built from hollow tube sections, 50.8 mm × 50.8 mm × 6.4 mm (2 in. × 2 in. × 1/4 in.), and plate sections, 6.4 mm (1/4 in.) thick, using adhesive bonding throughout. Hollow tube sections, a pair at the top and bottom, reinforce the web plates, such that the box-beam is essentially two built-up I-beams joined together by the top and bottom plates. Five internal diaphragms equally spaced at 800 mm, consisting of the same built-up I-beam components as for the webs, provide global lateral and torsional stability, as well as local stability to the top plate. Gusset plates, of the same plate material used throughout, connect the outer longitudinal tubes at the ends and the apex of the box-beam.

The hollow tubes and plates are pultruded sections with alternating layers of randomly oriented fibres and unidirectional fibre rovings in a vinyl ester resin matrix for the hollow tubes and an isophthalic polyester resin matrix for the flat plate. The amount of glass fibre by weight for these

sections is between 45 and 50%.

Figure 2 - Fabrication stage showing internal diaphragms

Table 1 lists the mechanical properties of the sections and adhesive. The low modulus of elasticity in both tension and compression are noted, as are the anisotropic properties of the sections. The orientation of all the main plates of the box-beam, namely top, bottom and web plates is with the unidirectional fibre rovings parallel to the longitudinal axis of the box-beam. In the webs of the internal diaphragms, the unidirectional rovings are parallel to the vertical axis of the box-beam. The longitudinal axis of the bridge is considered in the North-South orientation. Figure 2 shows the fabrication stage at which the internal diaphragms have been placed.

Figure 2 - Fabrication stage showing internal diaphragms

Table 1.. Material properties for GFRP sections and adhesive

Property		Hollow Tubes*	Plates**	Adhesive***
Tensile Strength (MPa)	LW	258.4	137.8	16.9
	CW	55.1	68.9	16.9
Young's Modulus (MPa)	LW	19 292	12 402	388
Compressive Modulus (MPa)	LW	19 292	12,402	92
	CW	8 268	6,890	92
Poisson Ratio	LW	0.36	0.31	0.4
	CW	0.36	0.29	0.4
Elongation	LW	n/a	n/a	55%
Shear Strength (MPa)		40[a]	41.3[c]	
		8[b]		15-20[d]

Notes:
LW: lengthwise parallel to the longitudinal fibres;
CW: crosswise direction which perpendicular to the longitudinal main fibres.
* Design Guide, Creative Pultrusions Incorporated.
PULTEX, Vinyl Ester 1625 Series, 45-50% fibre by weight
** Design Manual, Strongwell Company (formerly MMFG).
EXTREN - Flat Sheets Polyester 500/525 Series Standard Fibre Content
*** data sheets, Ashland Chemical Company. Pliogrip 6600/7700 Series.
[a] cross-sectional shear; [b] interlaminar shear; [c] perpendicular shear; [d] lap shear

Structural adhesive was used to connect the box-beam. Bolting was not considered, because of low connection failure loads for bolted FRP components in bearing, shear out, and tensile splitting [4]. However, bonding the components presented construction challenges that required meticulous quality control throughout fabrication. Therefore, the single-track box-beam was fabricated under close supervision in the structural laboratory at RMC. Owing to size and shipping limitations of the GFRP components, additional joints were introduced in both the web members and the bottom plates, with an attempt to locate these in zones of eventual lower stresses. The bonding area of the sections sanded, removing 1 to 1.5 mm of surface epoxy, until the glass fibres were exposed. The sanded surface was air blasted and solvent- wiped. The structural adhesive was applied to the prepared areas, and the components were joined with a constant adhesive thickness of 0.5 mm, achieved with round metal beads or electrical wire (both beads and wire having a 0.5 mm dia.). The components were clamped for four days until the structural adhesive was cured. The recommended clamping pressure was between 0.10 and 0.14 MPa (15 to 20 p.s.i.). Since the curing process took place at ambient temperature immediately following the application of the adhesive, it was essential to have the clamping applied as early as possible. Moreover, because long pieces of hollow tube and large pieces of flat sheets were involved, widely spaced small diameter bolts were also used to facilitate alignment of the members and clamping.

The design vehicle for the bridge will be an eight-wheel light armoured vehicle, having a gross weight of approximately 135 kN. Since deflection and stability criteria controlled the design of the single track box-beam, it was decided to test the box-beam under a much greater load than would be encountered due to vehicle loading. The laboratory tests to date consisted of patch loadings, applied sequentially in four locations, labelled MM, ME, TE, and SE in Figure 1. The patch load location MM is at midspan of the box-beam between the east and west webs. The patch load locations ME, TE, and SE are over the east web at midspan for ME and at the intermediate diaphragms, 800 mm and 1600 mm from midspan for TE and SE, respectively. The maximum test load for the MM location at mid-span, mid-width of the box-beam was 125 kN. For the other three locations, ME, TE, and SE, the maximum load was 110 kN. The laboratory tests were done initially on the structure without the grating wearing surface to de-couple the behaviour of the box-beam from that of the grating, and the structure was tested in three-point simply supported quasi-static loading.

3. FEM MODELLING

To support the development program it was decided to model the structure using a variety of FEM packages and specifically those targeted at supporting the design process. Initial models were made using plate and beam elements in a 3D model of the bridge using CSI's SAP 2000™ Non-Linear. Follow on models included a 3D solid model created using COSMOSWorks™. Due to the size of the 3D solid model it was initially derived for the MM load condition using two planes of symmetry, resulting in a ¼ bridge model. It was later expanded to a full bridge model for testing of the ME, TE, and SE load cases, however, computer limitations prevented the successful solution of the full-bridge models.

The SAP beam/plate model was limited to isotropic material properties. Properties representing the strong axis of the materials were input for each of the elements. Frame elements were used to represent the GFRP tubes, while shell elements were used to represent the various plates in the bridge. Full bond was assumed between the various elements of the model, except where the diaphragms supported the deck. Due to the knife-edge nature of the connection between the diaphragms and the deck it was assumed no rotational stiffness would be provided. The rotational degrees of freedom (DOFs) were released in these areas. The structure was modeled as simply supported, pinned across the south edge and a roller along the north edge. The load was applied as a pressure applied to the structure. The size of the load foot used for the MM load case was identical to that used in the laboratory by the hydraulic actuator. The load foot used for the eccentric load cases was reduced to avoid excessive deck deflections and better represent the constrained nature of the load application observed in the laboratory.

The COSMOSWorks model was created as a solid model using 8-noded linear-strain tetrahedral elements for the plates and tubes alike. Meshing was highly concentrated due to the thin nature of the structural elements. Maximum use of the iterative features available within the meshing algorithm had to be used to ensure a good mesh for each of the solid parts making up the model. The solid model used orthotropic materials properties throughout. Full bond was assumed between the various elements of the model. Consideration was given to modelling a less stiff rotational connection between the diaphragms and the top plate, but given the complex non-linear nature of the problem, it was left for follow on study. The structure was modeled as simply supported, pinned across the south edge and a roller used along the north edge. The ¼ model could not accommodate the difference in end conditions and was effectively pinned at both ends. The load was applied to a rigid loading plate added to the model. This load plate was constrained to force the load into the stiff frames and not cause excessive local deflections in the light deck plate. This better represented the nature of the loading used in the laboratory.

4. RESULTS AND DISCUSSION

Results from each of the FEM models reflected the behaviour observed in the laboratory reasonably well. The results of the SAP model, displaying stress contours superimposed on the deformed shape are shown in Figure 3. Stress contours superimposed on the deformed shape are shown in Figure 4 for the ¼ bridge COSMOS model.

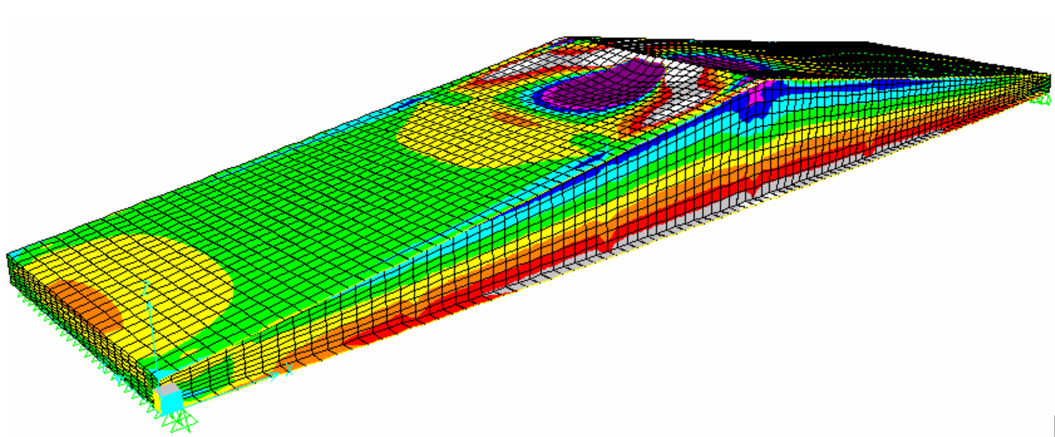

Figure 3 - Results of SAP Model showing stresses and deflections

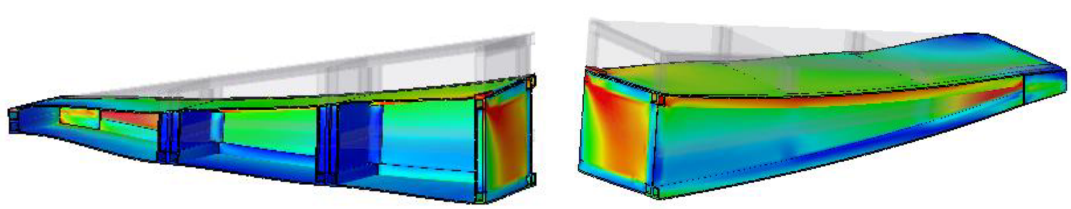

Figure 4 - Results of COSMOS Model showing stresses and deflections

The results obtained from the laboratory test at mid-span, without the grating wearing surface, confirmed that the load-displacement behaviour of the tapered box-beam was linear-elastic throughout. For test MM, at the maximum load of 125 kN, the deflection of the box-beam directly below the mid-span patch load was 24.6 mm. This compared favourably with the results of the analyses that predicted 26.6 mm (SAP) and 18.1 mm (COSMOS). This mid-span deflection corresponds to approximately l/200, where l is the span length. However, the patch load of 125 kN on the single track is over 90% of the gross vehicle weight, so that 125 kN is more than twice the total load expected in service, acting through the single patch load. Therefore the mid-span deflection would likely be better than l/400, which is acceptable. For test MM, the deflections below the outer two webs were both 23 mm, indicating good transverse stiffness at this section. The FEM models predicted between 16.0 mm (COSMOS) and 25.2 mm (SAP). Lateral displacements were also measured at mid-span and were negligible, suggesting also good lateral stability, as expected for a symmetrical, closed section.

At the maximum load of 110 kN for tests ME, TE, and SE, with the patch load placed over the east web as shown in Figure 1, the deflections at mid-span were highest for the east web. These were 29.7 mm, 27.3 mm, and 19.3 mm, respectively. These compared to values of 31.6 mm, 28.6 mm, and 18.5 mm for the SAP model. Figure 5 shows how the deflections at midspan varied across the section at mid-span for each of the load cases. For tests ME, TE, and SE, the west web deflected less than the east web, and indeed for test SE deflected upwards by some 3 mm. The deflections of the west web at mid-span for tests ME, TE, and SE were, respectively, 61%, 83%, and 114% less than those for the east web. While these values appear high, tests ME, TE, and SE are extremely severe edge loading tests that nevertheless confirm the good transverse load distribution and good torsional rigidity of the design. The SAP model predicted the deflections in the west web would be approximately 60% less than those in the east web regardless of the longitudinal position of the eccentric load. It appears that the SAP model overestimates the torsional stiffness and transverse load distribution of the structure. This is consistent given the simplified isotropic material properties used in the model.

Overall the COSMOS solid model gives a more stiff representation of the bridge than that observed in the laboratory, which is consistent with FEM theory. The accuracy of the model would be improved by reducing the rotational stiffness at the diaphragm / deck interfaces to something less than the full transfer assumed. The SAP model overestimated the deflections of the structure predicting a less stiff model than that observed. This is likely attributed to the fully released rotational DOF assumption used at the diaphragm / deck interface. In actuality there would be some limited moment transfer between the identified components.

Due to limitations of the computer to solve the larger solid models, the COSMOS models were limited in their usefulness to centered loads cases.

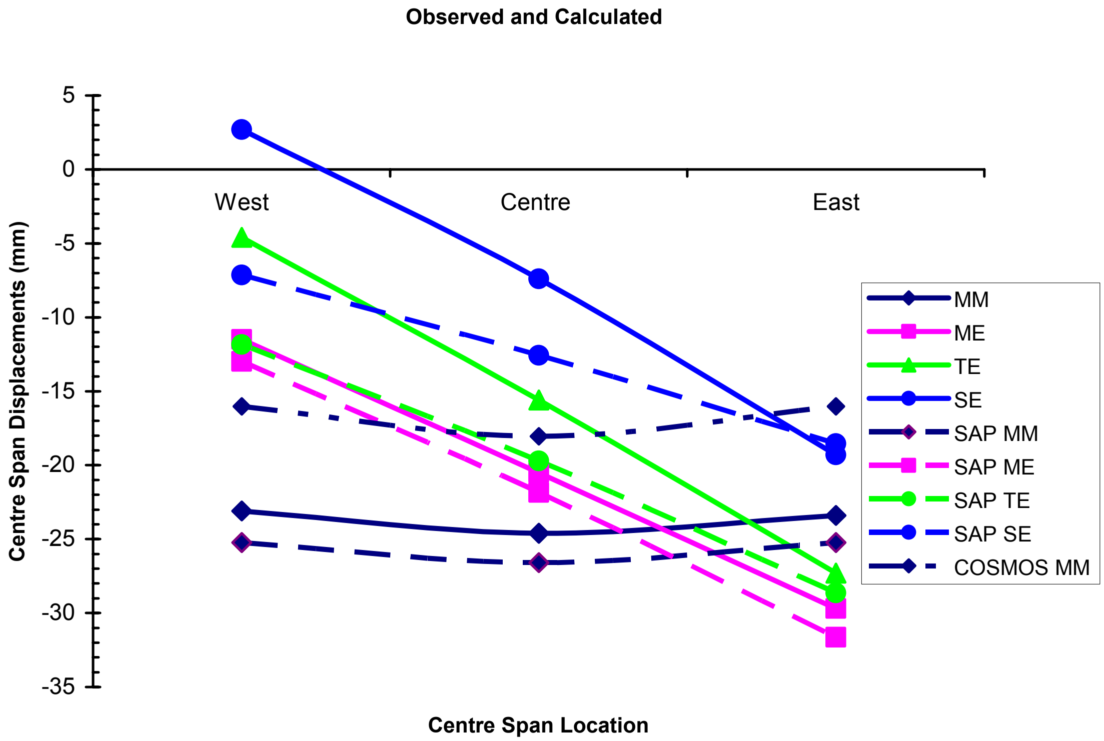

Figure 5 - Observed and Calculated Centre Span Displacements

5. CONCLUSIONS AND RECOMMENDATIONS

The FE models have demonstrated good correlation to the experimental observations for overall performance of the structure using material properties provided by the manufacturer. Detailed analysis of the joints is ongoing to ensure that any weakness in the detailed design is modified for prior to final prototyping.

The COSMOS FEM model provided reasonable, but stiff, results compared to that observed in the lab. This model was particularly useful when considering design options taking full advantage of the associated parametric modeler as well as the particularly useful pre- and post-processors. Despite the slightly longer solution times this model was very useful as a design FEM tool reasonably modeling the orthotropic materials and complex connections. Improved computer resources may make the larger models solvable for the eccentric loads.

The SAP frame/shell model gave very good and slightly less stiff results when compared to that observed in the lab. The model is less useful when looking at local failure modes due to the isotropic limitations on the material properties. Successive design iterations are not rapidly achievable, though each individual solution is quickly achieved once modeled.

The following future research work is proposed for the project:

FEM models will continue to be optimized including partial release of rotational stiffness at the diaphragm / treadway interface. FEM models will be used extensively to optimize the design of the second prototype prior to construction. Improved computer assets should allow for full 3D modeling of the full bridge.

Principal fibre directions in the structure will be optimised and hybrid fibre concepts will be studied for additional strengthening of the anticipated zones of critical stresses.

Based on the experience with the prototype box-beam, a full-scale two-track gap-crossing structure will be designed, constructed, and erected in an outdoor location for full-weight vehicle testing.

ACKNOWLEDGEMENTS

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