Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

8th International
Conference on Civil and
Architecture Engineering
ICCAE-8-2010

BEHAVIOR OF A MODULAR COMPOSITE ARMY BRIDGE UNDER FAILURE LOADS.

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Abstract

The Egyptian Army is interested in developing new light–weight short-span Composite mobile assault bridging systems that will greatly improve their tactical mobility (rapid deployment /retrievals,carry multiple bridges per launcher, minimum profile depth). In this paper, an overview of the behavior and Failure of a modular Composite Army Bridge is presented including; Army requirements, bridge design, analysis, and experimental testing program.

Finite Element Analysis (FEA) was used to get a detailed behavior of the modular Composite Army Bridge, as well as to predict the maximum load capacity, deflections, strains and failure modes. This paper summarizes the F.E. model used, analytical results, and the comparison with the experimental data.

KEY WORDS:

Composite, Analysis, Testing.

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1. Introduction:

The Egyptian Army is interested in developing new light-weight short-span mobile assault bridging systems. Most of the current bridging systems developed in the 1960's are not capable of carrying many of today's heavier tracked vehicles (MLC 70 vs older MLC 60) are not serviceable or upgradable [1], or are so heavy that they limit the force's mobility. The need for rapidly deployable light-weight bridging remains as important today as ever in order for armored vehicles and support vehicles to accomplish their mission. It has been shown by NATO obstacle plans of Western Europe[2] that through a combination of simple natural features and a coordinated plan of man-made obstacles that the mobility of an entire armored formation can be restricted, channeled, or even blocked. For the defender (home team), the creation of a coordinated obstacle plan is central to forcing the enemy to a prearranged target spot, while at the same time providing security from flanking maneuvers. For example, it was established that in the absence of bridges, 80% of water obstacles cannot be crossed or would prove difficult to cross even with modern water mobile vehicles and/or armored tracked vehicles. In most cases, it was not the depth of the water or the width of the gap, but rather the condition of the bank that stopped the vehicle. In fact, over 92% of the natural gaps in Europe and over 51 % of the natural gaps in Southeast Asia are less than 40. feet wide. In addition, almost a man-made obstacles of "tank-traps" are less than 30. feet wide. Thus, in these areas short-span bridging is just as important, if not more important than long-span bridging. Currently within the United States military there is a need for a light-weight bridging system for crossing short-span gaps up to 4 m (157 in.) in length. This bridge must also have a low profile constant thickness of 100 mm (4 in.) or less, such that it can be used for other applications including decking for long span modular bridging, roadway matting, overlays for damaged bridge decks, and loading ramp systems for aircraft and ships. Moreover, it is required that the bridging system support Military Load Class 30 (MLC 30, 27,000 kg, 60,000 lbs) track vehicles and palletized load system (PLS) truck vehicles under extreme environmental and bank support conditions. For comparison purposes the HS-20-44 truck prescribed by the American Association of State Highway and Transportation Officials (AASHTO) would have a MLC rating between 25 and 30 resulting in maximum moments and shears which are about 10% lower than that produced by an MLC 30 rated vehicle and 15% less than a fully loaded PLS truck.To address the need for short-span bridging, MAN mobile bridges, located in Germany, has developed a commercially available mobile bridge known as the short track bridge (STB) which is capable of spanning gaps up to 4 m in length while supporting MLC 30 vehicles. The bridge is composed of two parallel treadways fabricated using high strength aluminum. Each treadway is 5.2 m (205 in.) long and 0.6 m (24 in.) wide, with the bridge depth varying along the length having a midspan maximum depth of 0.28 m (11 in.). A single treadway weighs 250 kg (550 lbs) with the full bridge weighing 500 kg (1,100 lbs). Recently Wight et al. (2006) presented the development and testing of a FRP short-span bridge developed for the Canadian Forces (CF). The bridge consists of two treadways fabricated from pultruded fiberglass tube sections and sheets which are bonded together to form a tapered box beam (treadway) which is 4.8 m (189 in.) long and 1.2 m (48 in.) wide. As with the aforementioned MAN bridge, the bridge depth varies along the length from 0.1 m (4 in.) at the ends to 0.5 m (20 in.) at the midspan. A single treadway weighs 500 kg (1,100 lbs) and is designed to carry a vehicle weighing 27,000 kg (60,000 lbs). This weight does not include a wear surface or launching hardware.

Since the 1990s the United States Army has been interested in developing new light-weight mobile bridging systems to replace existing heavier mobile bridging systems which are near the end of their service life. As part of this bridge replacement effort the United States Army desired a new bridging system which was capable of crossing gaps up to 12.2 m (40 ft) in length while supporting track and wheeled vehicles up to MLC 100 (90,700 kg, 200,000 lbs). To meet this need, a technology demonstration bridging system known as the composite Army bridge (CAB) was developed and tested at the University of California, San Diego, and University of California, IRVINE. The bridge is composed of a carbon/epoxy substructure with a balsa core sandwich deck.

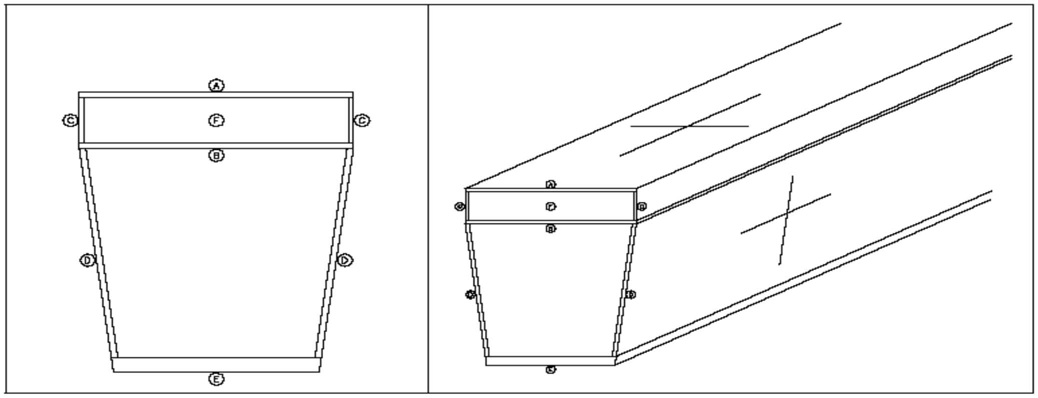
This paper presents a study of the detailed behavior of the modular Composite Army Bridge, consisting of hollow box beam with a total span of 12 feets. The specimen was simply supported and loaded using two concentrated line loads, 32 inches apart, at the middle third of the specimen. The dimensions of the tested beam are shown in figure (1). The progressive failure analysis finite element GENOA software is utilized to get a deep insight of the stress and strain distribution in the bridge, and the maximum deflections reached as well as the mode of failure. The testing procedure and experimental results are performed at the Structural Engineering Testing Hall (SETH) of the Department of Civil & Environmental Engineering at UCI. A comparison between theoretical and experimental results regarding strains and deflections is provided.

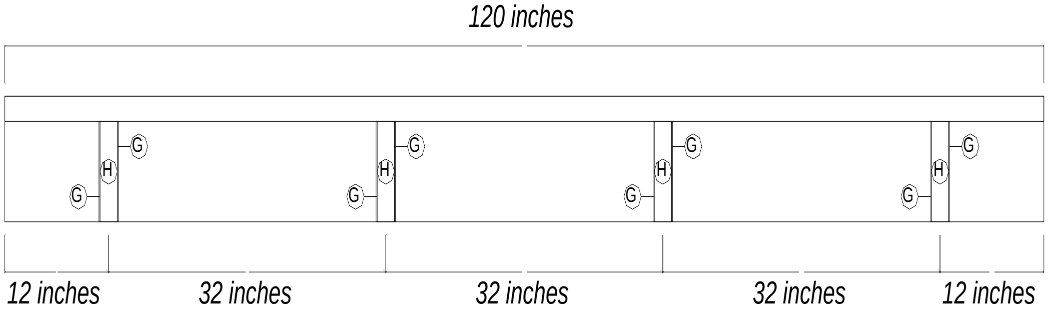
2.Requirements:

The design of the bridge treadway system is driven by performance requirements provided by the United States Army and outlined in the Trilateral design and test code for military bridging and gap-grossing equipment TDTC 2005 (Hornbeck et al. 2005). The TDTC is a design and test code for military gap-crossing equipment which was developed through a cooperative effort between the United States, Germany, and the United Kingdom. The intent of the code is to provide a common set of design and testing procedures as well as requirements which allows equipment (bridges) tested in one country in accordance with the TDTC to be suitable for international acceptance. The requirements are: (1) The bridge treadways must be light enough to be handled by military personnel without the assistance of heavy lifting equipment such as cranes or forklifts; (2) the treadways need to support both MLC 30 track and PLS truck vehicles over a 4 m (157 in.) gap; (3) the treadways shall have a maximum constant depth of 100 mm (4 in.); (4) the treadways must be wide enough to be safely crossed by the prescribed vehicles; (5) the maximum deflection of the treadways under full working load is to be limited to 152 mm (6 in.) (to maximize weight savings, allowable deflections for military bridges are significantly higher than those for civil bridges); (6) a minimum safety factor of 1.5 with respect to S-basis material strength properties shall be maintained for all components of the treadways; and (7) the treadways must be capable of performing under temperatures ranging from -46°C (-50°F) to71°C (160°F). Additional gap crossing site criteria found in the TDTC 2005 (Hornbeck et al. 2005) require that the bridge be designed to perform at sites in which: (1) The bank soil maximum bearing pressure is 380 kN/m2 (8 kips/ft2); (2) the slope from the near to far bank is ± 1:10; and (3) the transverse slopes of the near and far banks are up to 5% (10% relative slope if each bank slopes in opposite directions). Due to the short length of the treadways the transverse bank slope requirement was relaxed to a total relative slope between the near and far banks of 5%.

3. DESIGN ISSUES:

The design of the the modular Composite Army Bridge evolved to a hollow box beam which is characterized by a superstructure and a deck.The dimensions of the tested beam are as shown in figure (1). the total span of the beam is 12 feets. The upper and lower surface of the top deck consist of 8 plys of CFRP with a thickness 3/16 inch for each with a balsa core used as a sandwitch between the two layers of the upper deck with a thickness 1.75 inch. To provide a good compression stifness to the upper deck and to decrese the total weight of the beam, the plys of the two layers of the upper deck are oriented with varying angles ranged from (0^o to 90^o) to provide stability for the upper deck of the bridge, the primary side walls of the beam consist of 8 plys of CFRP with a total thickness 3/16 inch for each side wall, the plys are oriented with varying angles ranged from (-45^o to 45^o) to provide stability and increase the shear strength for the beam ,the lower flange (surface) consist of 12 plys of CFRP with a total thickness 1/2 inch, the plys of loer flange are oriented with varying angles ranged from (0^o to 90^o) to increase both the tensile and flexural strength of the beam, four balsa bulkhead with a thickness 2 inches for each bulkhead wraped with six layers of CFRP at each side with a thickness 1/4 inch for each to provide torsional stability for the beams. The beams were tested under monotonic loading up to failure using displacement control.





			FIBER ARCHITECTURE			
member	**reference**	**thickness**	**0°**	**90°**	**+45°**	**-45°**
A	top deck	3/16	85 %	15%	0 %	0 %
B	lower surface balsa core	3/16	100 %	0 %	0 %	0 %
C	balsa core sidewall	3/16	50 %	50 %	0 %	0 %
D	primary sidewall	3/16	0 %	33 %	33 %	33 %
E	lower surface	½	90 %	10 %	0 %	0 %
F	balsa core	1 ¾	Balsa Wood			
G	bulkhead wrap	¼	50 %	50 %	0 %	0 %
H	balsa bulkhead	2	Balsa Wood			

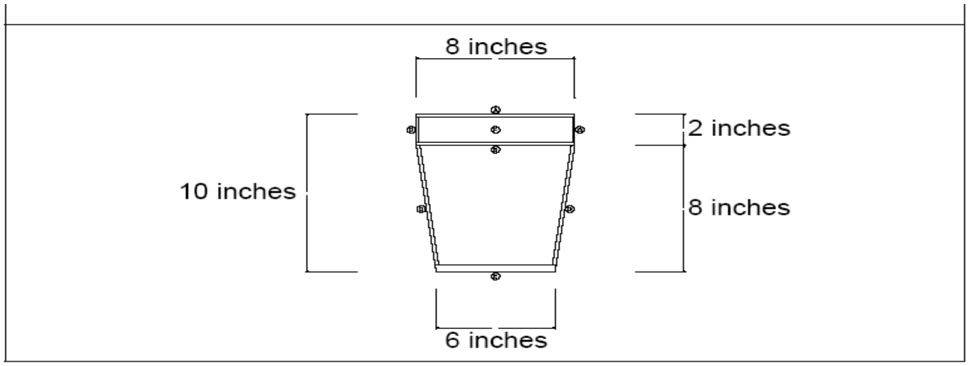


Figure (1): Geometry, Thicknesses and Fiber Architecture of Test Specimens.

4. Material properties and fabrication:

The specimen is completely manufactured by (Composite Structures Manufacturing / Watertronics.) Factory in California under the control of the Civil & Environmental Engineering Department of California University at Irvine (UCI),and Alpha Star Group for structural software members using a wet lay-up and vacuum bagging process as shown in figure (2a) up to figure (2d).

Figure (2a): Mold utilized to manufacture the bridge components.

Figure (2b): Top Cap of the bridge.

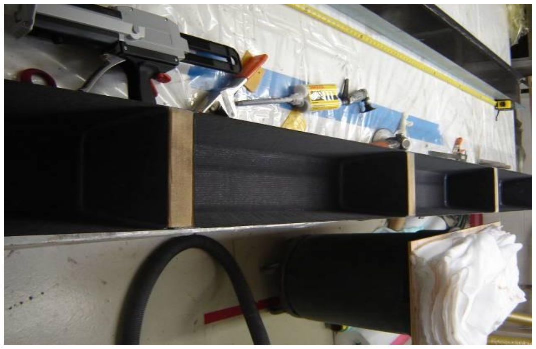


Figure (2c): The lower cavity and bulkhead of the bridge.

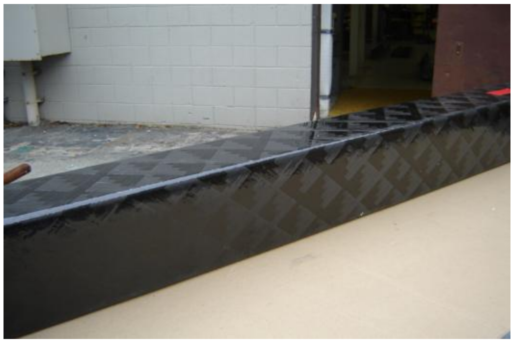


Figure (2d): Completed Beam after Filament Winding .

The top cap is constructed of 20 oz Bi-Directional Carbon woven by Fabric Development, while the lower cavity and bulkhead skins are produced from Vectorply C-TTX 3600 36 oz triaxial carbon fiber cloth. Then the whole specimen is wounded with 2 layers of +/- 45 Degree of Grafil Pyrofil 12K carbon fiber using filament winding process. The resin used for bounding the bridge components is Epon 862 Epicure, Mechanical properties of the materials used for manufacturing the specimen components are shown in Table (1). and Table (2)

Table 1. Mechanical properties of Carbon Fibers.

property	Triaxial	Unidirectional	Biaxial
Weight Denisty(lbm/in3)	6.4E-02	6.4E-02	6.4E-02
Normal Modulus(11) (lbf/ in2) E11	3.2E07	3.05E07	3.2E07
Normal Modulus(22) (lbf/ in2) E22	2.5E06	2.4E06	2.5E06
Poisson,s Ratio (12) V12	2E-01	2E-01	2E-01
Poisson,s Ratio (23) V23	2.5E-01	2.5E-01	2.5E-01
Shear Modulus(12) (lbf/ in2) G12	6.0E06	6.0E06	6.0E06
Shear Modulus(23) (lbf/ in2) G23	6.0E06	6.0E06	6.0E06
Coef. Thermo. Exp (11)	-3.89E-7	-3.89E-7	-3.89E-7
Coef. Thermo. Exp (22)	6.47E-6	6.47E-6	6.47E-6
Tension Strength (lbf/ in2) Xt	3.4E05	4.4E05	3.4E05
Compression Strength (lbf/ in2) Xc	1.20E05	3.75E05	2.0E05

Table 2. Mechanical properties of Epon 862 Epicure Resin.

property	Epon 862 Epicure

	Resin.
Weight Denisty(lbm/in3)	4.57E-02
Normal Modulus (lbf/ in2)	5.7E05
Poisson's Ratio	3.5E-01
Coef. Of Thermo. Exp	2.88E-05
Tension Strength (lbf/ in2)	6.5E03
Compression Strength (lbf/ in2)	3.9E04
Shear Strength (lbf/ in2)	7.50E03
Longitudnal Tension Strain	0.00
Longitudnal Compression Strain	0.00
Shear Strain	0.00
Melting Temp.	5.72E02

5. EXPERIMENTAL PROGRAM:

The Experimental program was performed at the Structural Engineering Testing Hall (SETH) of the Civil Department & Environmental Engineering at UCI, where the specimen is consisting of a hollow box beam,the clear span of the specimen is 8 feets with an overhang of 12 inches at each end. Dimensions of the tested specimen were 8 inches wide at the upper cap, 6 inches at the lower cap and 10 inches deep with an overall length of 12 feets. The specimen was simply supported and loaded using two concentrated line loads, 32 inches apart, at the middle third of the specimen as shown in Figure 3. The specimen was loaded using Loading system employed a 55000 lbs MTS hydraulic actuator. The load was applied under a displacment control at a rate of 2000 lbs/min. A National Instruments PXI-1042Q data acquisition system was used to collect the data at a rate of 1 sample /sec.

The specimen was instrumented as shown in Figure. 4. To record the longitudnal and transverse tension and compression strains in addition to the shear strain, the load and stroke of the testing machine.The longitudinal strains of the modular Composite Army Bridge were measured using electrical strain gauge produced by Kyowa measuring instruments co. LTD Tokyo, Japan of the type KFG-10-120-C1-11, which has the following characteristics:
gauge length = 10-mm, gauge resistance =119.8 ±0.2 ohm, gauge factor = 2.11±1.0%, adaptable thermal expansion = 11.7 PPM/c° and transverse sensitivity =0.2 %. The applicable gage cement cc-33A,Pc-c was used to stick the strain gages on the CFRP laminates after cleaning and smoothing the surface.

Figure (3): Test setup.

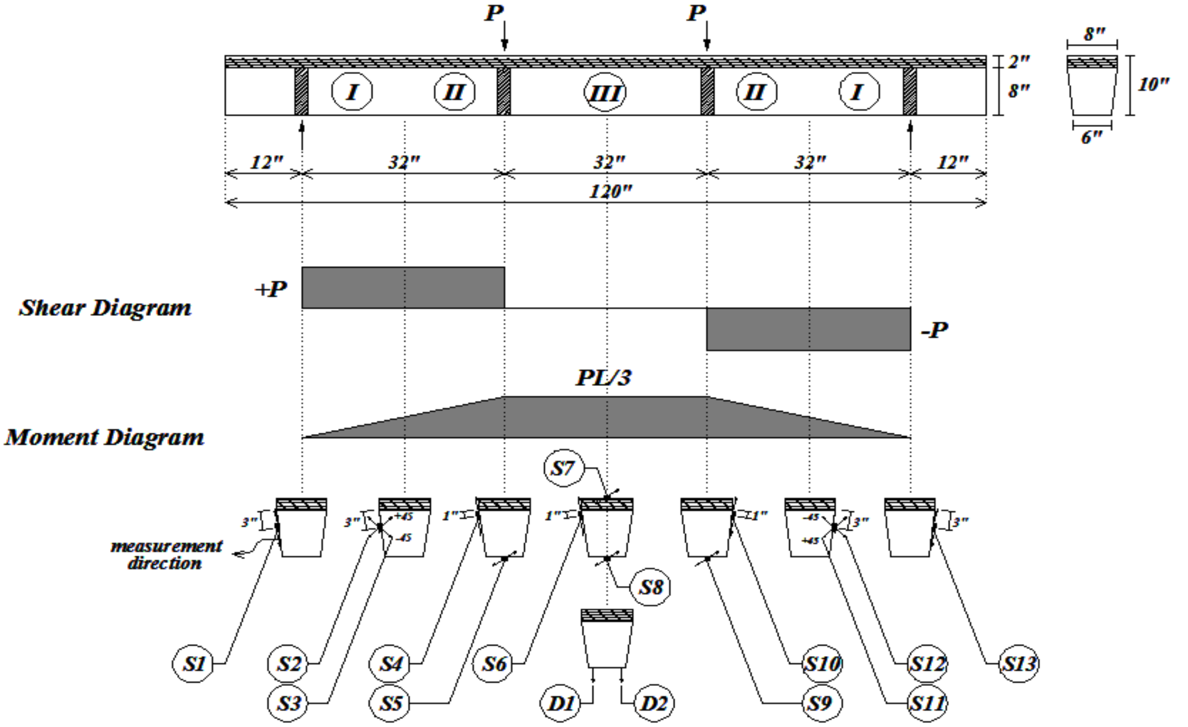
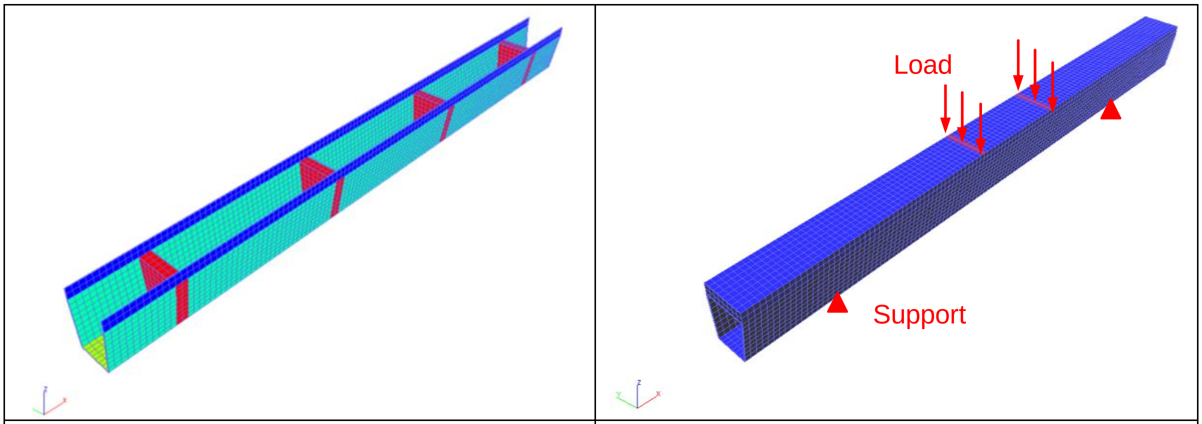


Figure (4): Specimen Instrumentation.

6. STRUCTURAL ANALYSIS:

The FEM model of smart bridge consists of 6,964 nodes and 5,952 elements, including laminate elements to model the upper surface Balsa, Primary sidewall, and Lower surface, and solid elements to model the Balsa core and Balsa bulkhead. (Figure) This model is based upon the UC Irvine’s design. 4 point bending loads were applied on the model with displacement control.

The model is used to: (1) compare the stiffness, displacement, and strain values in the linear loading region, and (2) compare and assess the analytically predicted failure load to the experimentally measured failure load.



(a) FEM model display without top deck and balsa core

(b) Boundary conditions

Figure 5. FEM Model of Modular Composite Army Bridge.

7. EVALUATION OF THE EXPERIMENTAL DATA:

As the load was increased, at 15 kips, the first crackling sounds were heard at this experiment and continuous and even louder crackling sounds were heard at higher load levels. A huge crackling sound was heard at the approximate load of 33 kips which was followed by failure of the bridge specimen at 34.91 kips. No localized damages occurred to the upper sandwich portion of the section at any loading point and the failure of the bridge specimen happened due to the instability at the location of an intermediate bulkhead at a loading point. The failure mode of this specimen is shown in Figure (6).

- In most cases a linear relationship is present between the load and the measured strains and displacements up to the failure of the specimen as shown figure (7a) up to figure (7h).
- From the curve of load versus Strain S4, it is seen that the transverse strains on the side walls at the loading points have initially been compressive, while approximately at the load 23 kips they have changed from compression to tension. This is indeed due to the out-of-plane deformation or localized distortion of the side wall at the loading points.
- Note that S6 has interestingly revealed tension transverse strains instead of compression strains. It can be inferred that at zone III with pure bending behavior and maximum compression, the thin-walled side walls of the section have had an out-of-plane deformation due to excessive compression at this zone.

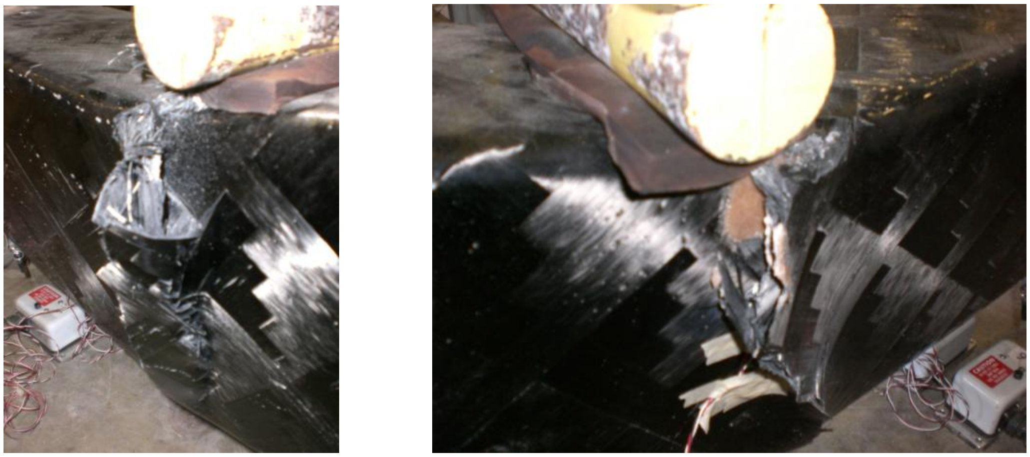


Figure (6): Failure of modular Composite Army Bridge.

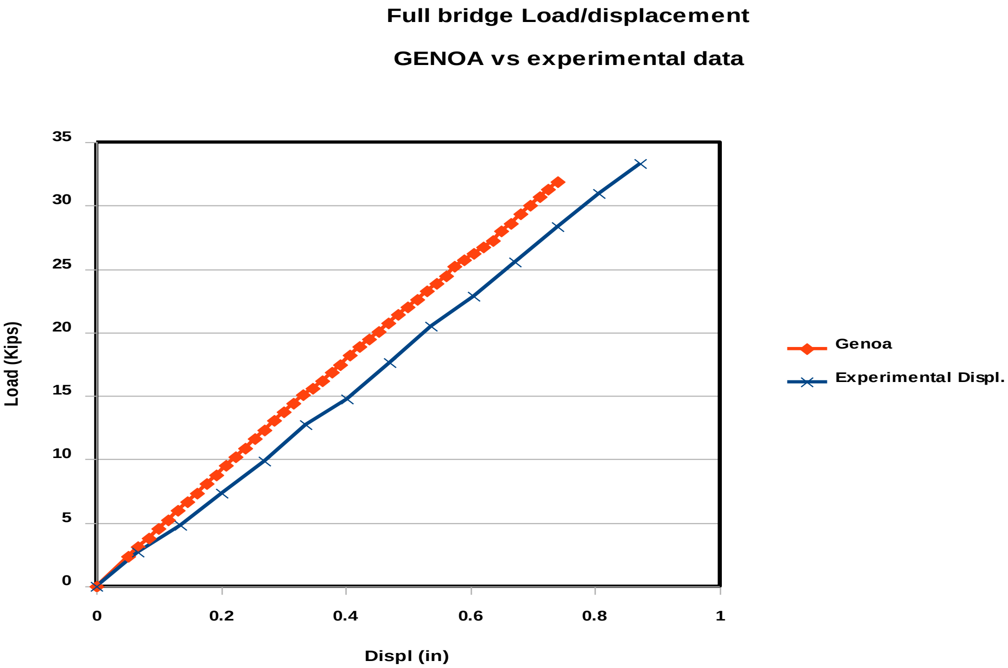


Figure (7a): Full bridge Load/ Displacement(Genoa vs Experimental data).

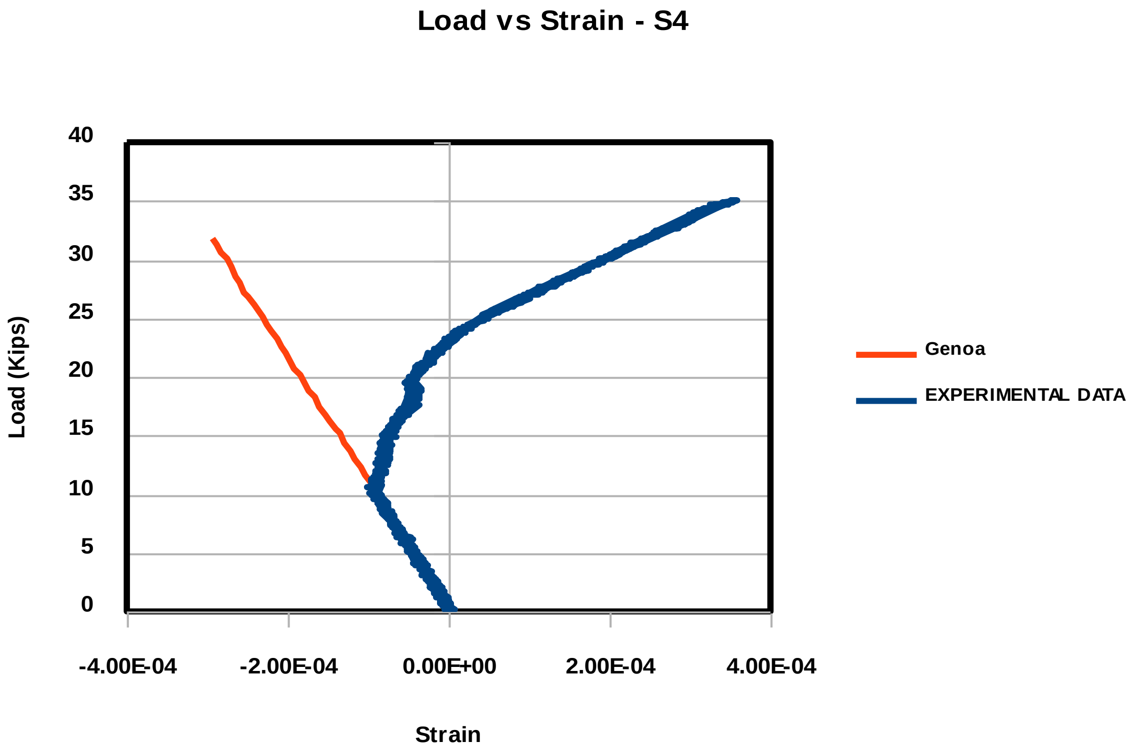


Figure (7b): Full bridge Load/ Strain S4 (Genoa vs Experimental data).

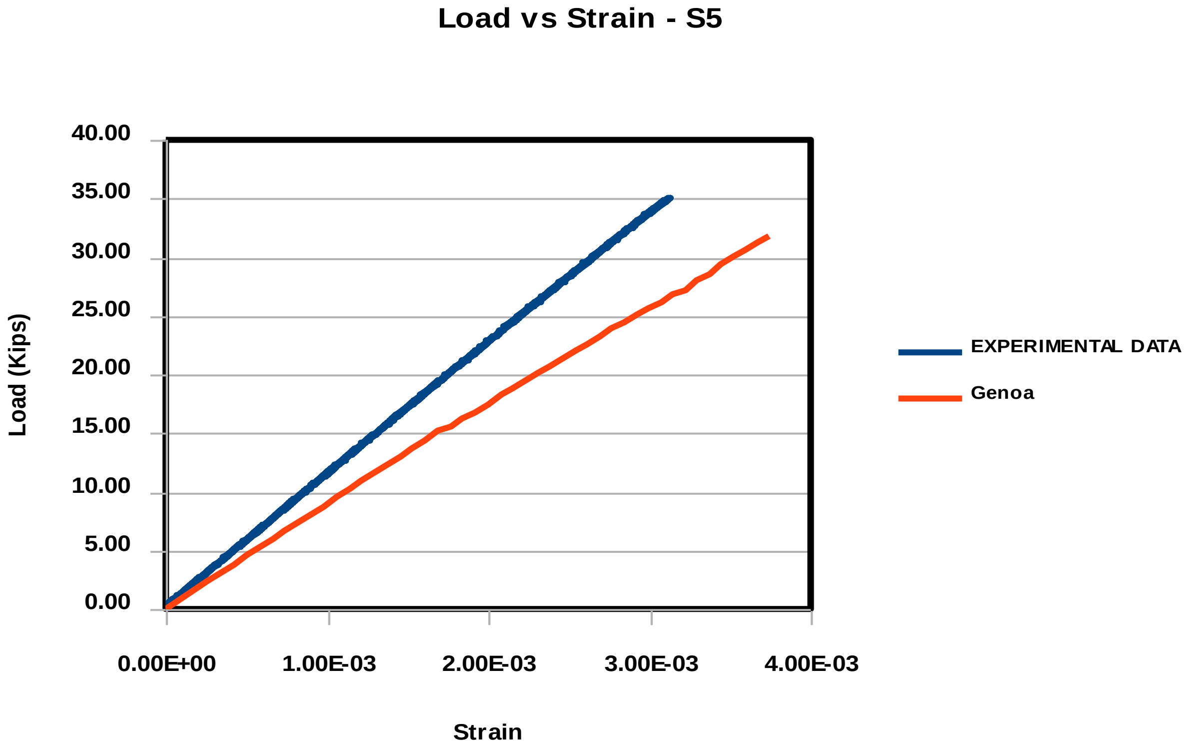


Figure (7c): Full bridge Load/ Strain S5 (Genoa vs Experimental data).

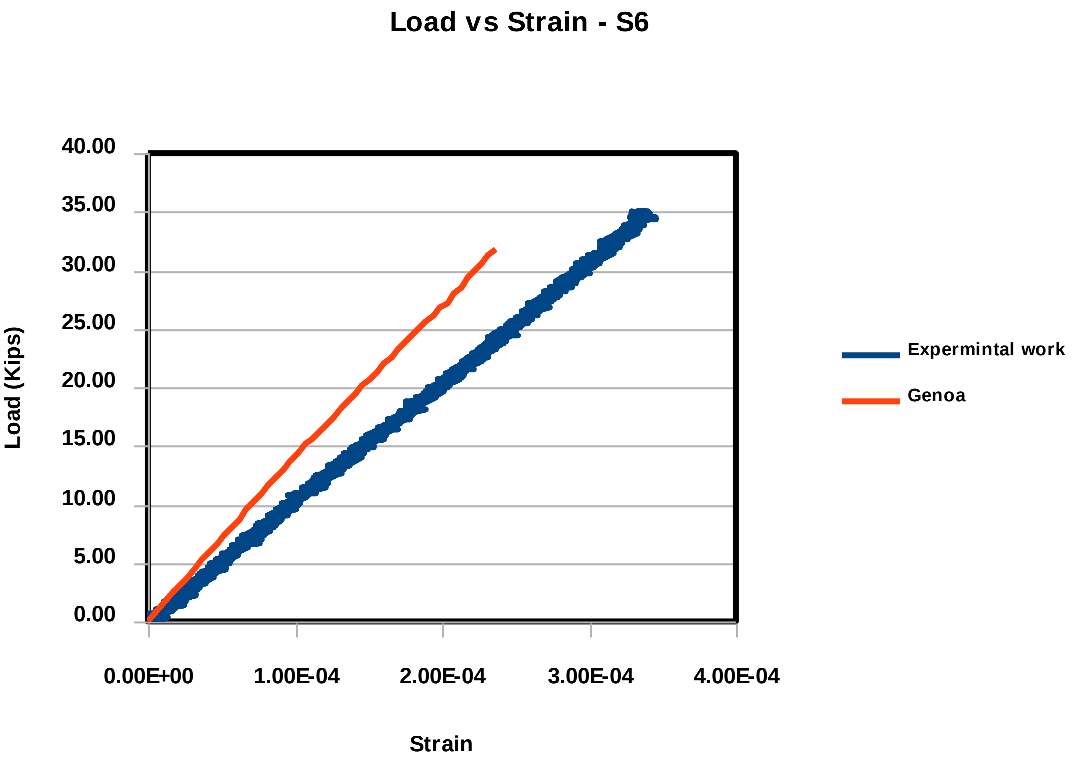


Figure (7d): Full bridge Load/ Strain S6 (Genoa vs Experimental data).

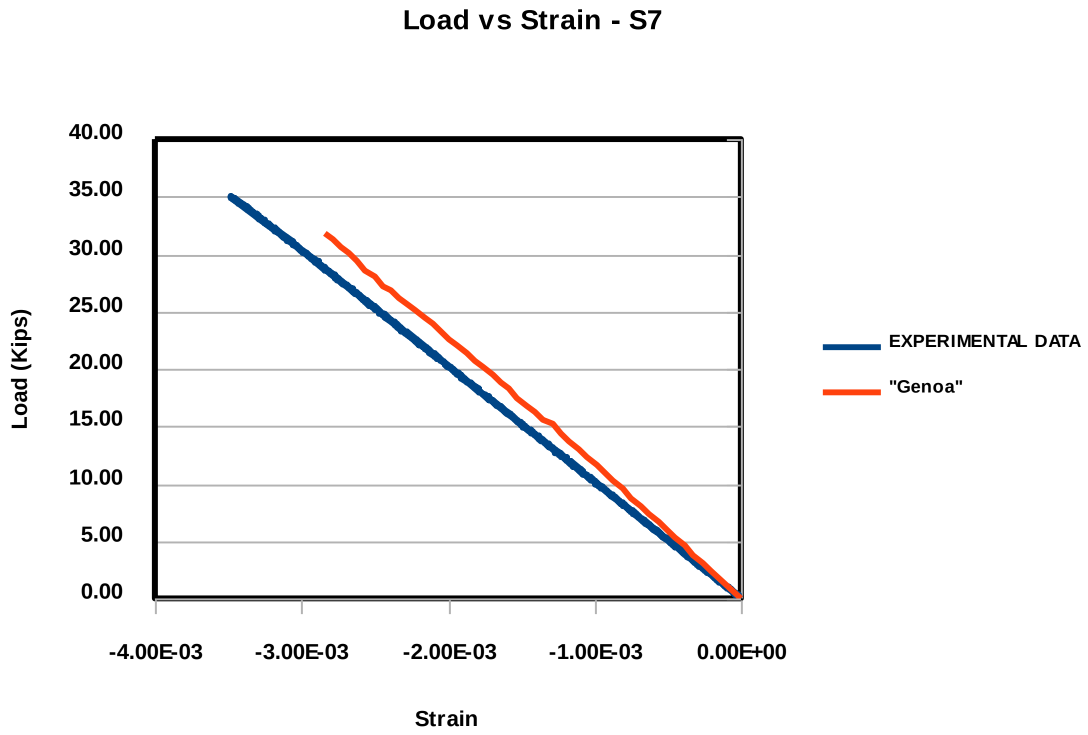


Figure (7e): Full bridge Load/ Strain S7 (Genoa vs Experimental data).

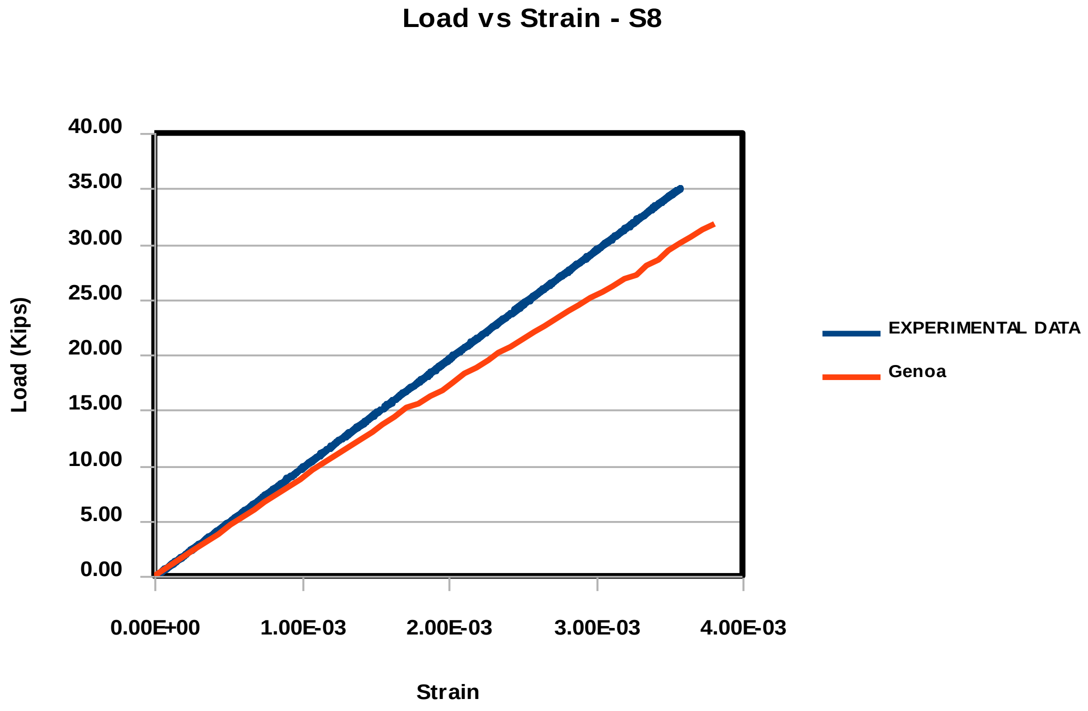


Figure (7f): Full bridge Load/ Strain S8 (Genoa vs Experimental data).

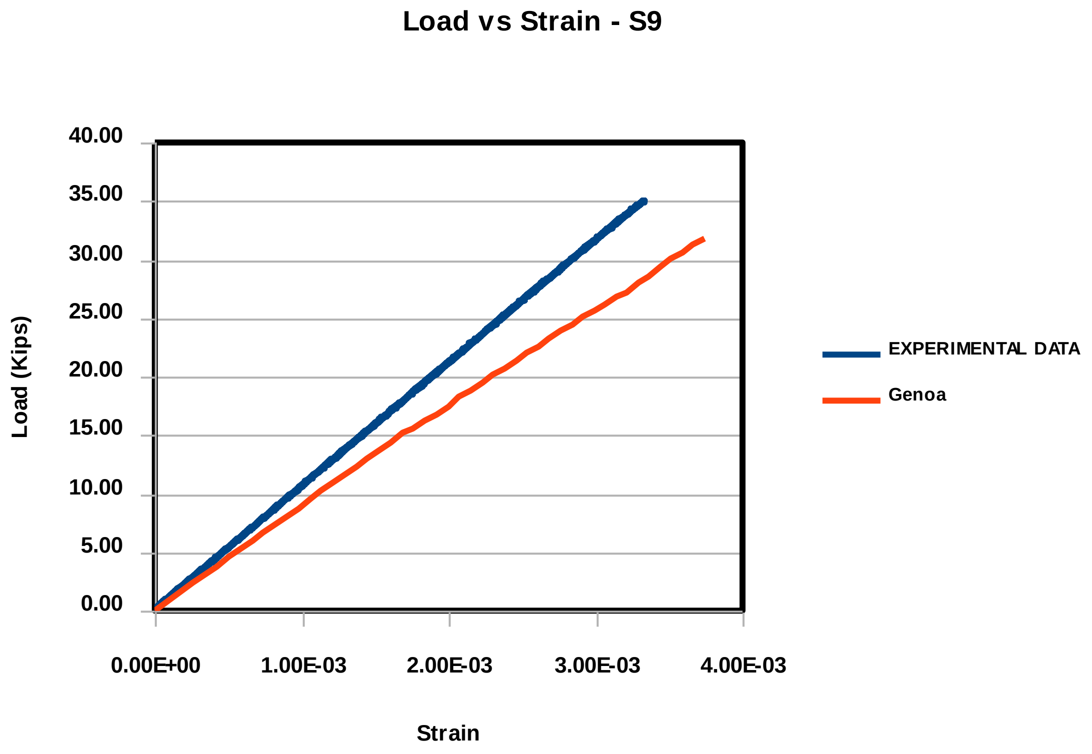


Figure (7g): Full bridge Load/ Strain S9 (Genoa vs Experimental data).

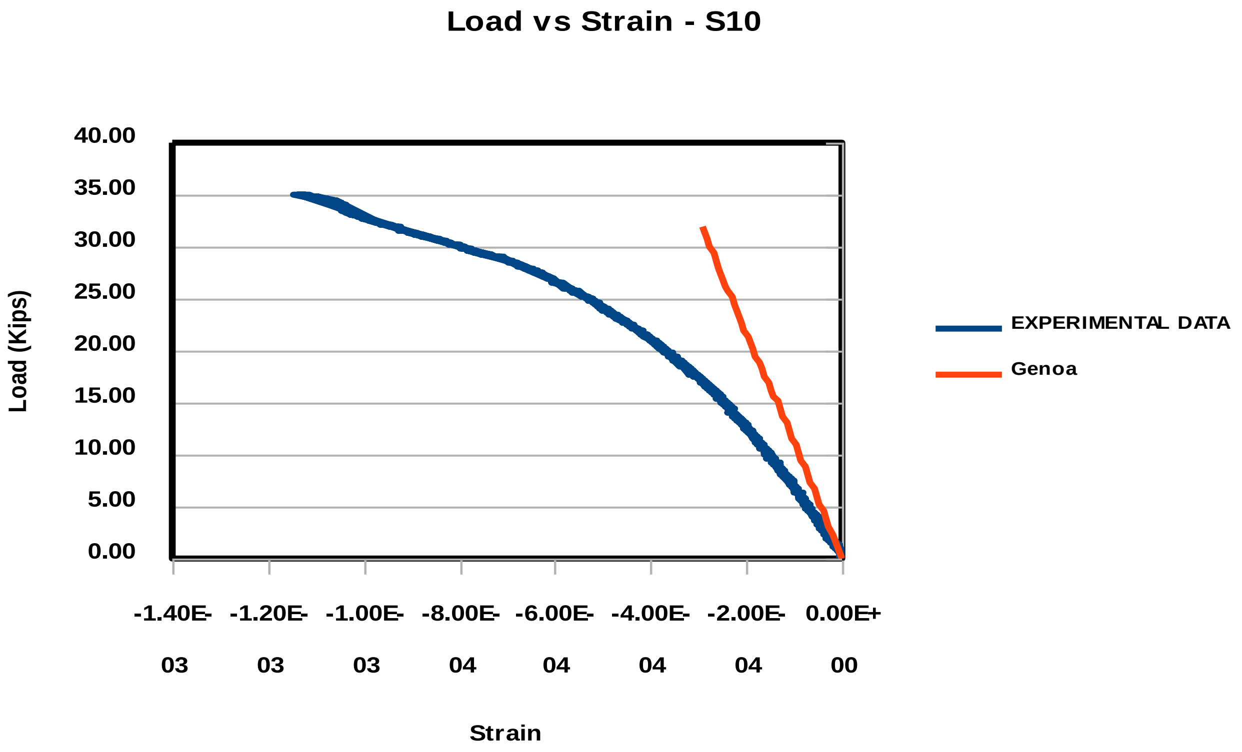
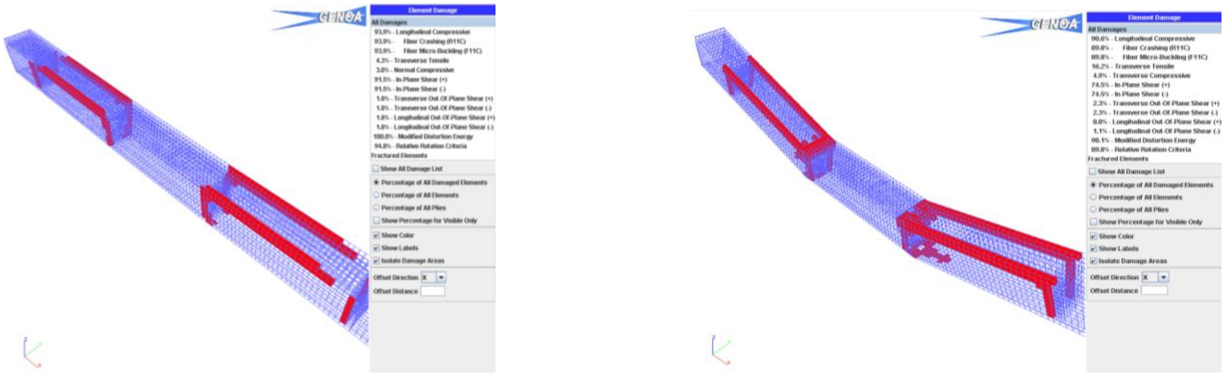


Figure (7h): Full bridge Load/ Strain S10 (Genoa vs Experimental data).

7.COMPARISON WITH THE ANALYTICAL PREDICTIONS.

- Based on the results of the analysis by GENOA, the damage on the bridge initiated after reaching 33 kips load level, which resulted in the dramatic stiffness degradation of the structure. The damage is mainly due to the longitudinal compressive criteria and in-plane shear criteria around the bulkhead core at the beginning of damage propagation. Subsequently, fractures occurred at the bulkhead core, and destroyed the support of the box bridge in the center. Therefore, the 33 kips lbs load was considered as the failure load of the modeled bridge as shown in figure (8a) and figure (8b).
- The ultimate failure load of the bridge is approximately 33 kips, while the ultimate experimental failure load is 34.9 kips.
- The amount of the in-plane (downward) deflection at the ultimate failure load based on the GENOA analysis is about 0.8 in, while the similar amount acquired from the test is about 0.9 in.
- The amount of the maximum tension strain recorded at the lower surface of the section at midspan is found to be 0.35% based on the experimental data.



All Damages
93.9% - Longitudinal Compressive
93.9% - Fiber Crashing (R11C)
93.9% - Fiber Micro-Buckling (F11C)
4.3% - Transverse Tensile
3.0% - Normal Compressive
91.5% - In-Plane Shear (+)
91.5% - In-Plane Shear (-)
1.8% - Transverse Out-Of-Plane Shear (+)
1.8% - Transverse Out-Of-Plane Shear (-)
1.8% - Longitudinal Out-Of-Plane Shear (+)
1.8% - Longitudinal Out-Of-Plane Shear (-)
100.0% - Modified Distortion Energy
94.8% - Relative Rotation Criteria
Fractured Elements
☐ Show All Damage List
● Percentage of All Damaged Elements
○ Percentage of All Elements
○ Percentage of All Plies
☐ Show Percentage for Visible Only
☑ Show Color
☑ Show Labels
☑ Isolate Damage Areas
Offset Direction X
Offset Distance

All Damages
98.6% - Longitudinal Compressive
89.8% - Fiber Crashing (R11C)
89.8% - Fiber Micro-Buckling (F11C)
16.2% - Transverse Tensile
4.9% - Transverse Compressive
74.5% - In-Plane Shear (+)
74.5% - In-Plane Shear (-)
2.3% - Transverse Out-Of-Plane Shear (+)
2.3% - Transverse Out-Of-Plane Shear (-)
0.8% - Longitudinal Out-Of-Plane Shear (+)
1.1% - Longitudinal Out-Of-Plane Shear (-)
98.1% - Modified Distortion Energy
89.8% - Relative Rotation Criteria
Fractured Elements
☐ Show All Damage List
● Percentage of All Damaged Elements
○ Percentage of All Elements
○ Percentage of All Plies
☐ Show Percentage for Visible Only
☑ Show Color
☑ Show Labels
☑ Isolate Damage Areas
Offset Direction X
Offset Distance

(a) Damage propagation (Load = 31 kips) (b) Damage propagation

(Load = 33 kips)

Figure (8): Failure load of the modeled bridge**.**

8.CONCLUSION

- The laboratory test confirmed that the load displacement behavior of the modular Composite Army Bridge was linear elastic to the maximum test loads.
- At the maximum test loads, the displacements were acceptable, and the tests showed good transverse stiffness and good lateral stability.

- Although there is no remarkable difference between the two deflections at the ultimate failure loads, but the disparity between the experimental and analytical ultimate failure loads is considerable which may be attributed to the existence of the initial geometric and material imperfections, uneven test setup, etc.
- As a comparison between different resins epoxy (Shell Epon 862 Epicure) provided the best tension, compression and shear properties.
- Military composite bridges offer many unique advantages for the army including :
  - lightweight (high strength-to-weight ratio).
  - superior corrosion resistance properties that are preferred in harsh environmental conditions.

9. ACKNOWLEDGEMENT:

- The writers would like to express their deepest gratitude to all staff who shared effort in producing this paper especially the Department of Civil & Environmental Engineering of University of California at Irvine (UCI),and Alpha Star Group for structural software members.

REFERENCES:

Abdi, F., Surdenas, J., Mosallam, A., and Wang, J.J., Field Repair Technology For Composite Bridges, Final Report, Phase I 2003 (Submitted to US Army – TACOM).

Bustin, I., "Military Bridging Programmes for Armored Vehicles," Military Technology, vol. XVII, Issue 2, pp. 50-61, February, 1993.

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

Chamis, C.C., Failure Criteria for Filamentary Composites, Composite Materials Testing and Design: ASTM STP 460, 1969 (American Society for Testing and Materials).

Mosallam, A., Ramki Iyer, and Abdi, F., Progressive Failure Analysis of Composite Army Bridges, 2005 (CICE Publications: Australia).

Ramki Iyer, Mosallam, A., and Abdi, F., Progressive Failure Analysis of Composite Army Bridge, in The Second International Conference on FRPComposites in Civil Engineering, Adelaide, 2004.

Shehata, E., and Rizkalla, S. (2003). “Filament-wound Glass Fiber Reinforced Polymer bridge deck modules.” *J. Compos. Constr,*7(3), 266-273. Zureick, A., Shif, B., and Munley, E. (1995). “Fiber-reinforced polymeric bridge decks.” *Struct. Eng. Rev.*, 7(3), 256-266.

Trilateral design and test code for military bridging and gap-crossing equipment (TDTC). (2005). Trilateral Design and Analysis Group of the United States, Germany, and the United Kingdom, January.

Tsai, S.W., Strength Theories of Filamentary Structures. In Fundamental Aspects of Fiber Reinforced Plastic Composites, edited by R.T. Schwartzand H.S. Schwartz, 1968 (Interscience: New York).

Wight, R. G., Erki, M. A., Shyu, C. T., Tanovic, R., and Heffernan, P. J.(2006). “Development of FRP Short-Span Deployable Bridge—Experimental results.” *J. Bridge Eng.,* 11(4), 489-498. Williams, B.,