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Design and Testing of Carbon Fiber Reinforced Polymer Foldable Tapered Bridge Beam

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Abstract: There is a need for lightweight and robust portable bridge that able to span the gap up to 28 m and supporting vehicles load of minimum 30 ton in total weight. The structure can be utilized in military or disaster relief operations. Therefore, a portable bridge that consists of two foldable beams was developed using Carbon Fibre Reinforced Polymer (CFRP) and Aluminium Honeycomb. Each beam consists of three sections connected by steel joints that allow the beam to be folded for storage and mobility. This paper describes fabrication process using wet hand lay-up method and structural testing of the scaled-down beam prototype to investigate performances of the beam, including maximum deflections, strains on the beam as well as maximum failure load. Wet hand lay-up method is chosen due to simplicity in the prototype production process where special equipment such as autoclave is not required. Further, it utilised available materials in the market, i.e. carbon fibre, epoxy, and aluminium honeycomb. As for the performances, it was found that maximum allowable load that can be supported by the 20% scaled-down prototype beam of 6 meter span is 11.3 kN, while the failure load is 12.9 kN. The failure load is defined relative to excessive deflection that occurs during the test. Deflection at the maximum allowable load of 11.3 kN is 68 mm or L/88, while deflection at the failure load of 12.9 kN is 156 mm or L/38. The calculated actual capacity of the full-scale 30 meter beam, including impact factor of 1.2, is targeted around 235 kN. Consequently, the bridge, with 2 beams, can carry ultimate load of up to 470 kN or 47 ton, or equivalent to Military Load Class, MLC50.

Key words: Portable Bridge, Portable beam, CFRP, Wet hand lay-up, Structural testing

INTRODUCTION

Portable bridges usually needed to span natural gap such as river, valley or artificial gaps such as road craters, or new gaps due to natural disasters. The use of conventional materials, i.e. steel or concrete, will produce a very heavy bridge which is not suitable for requirements of portable bridging system. The use of lightweight materials such as aluminium alloy and fibre reinforced polymer (FRP) are expected to produce light-weight bridging system that can be deployed and retrieved using minimal manpower and equipment.

There are always needs for lightweight bridging system that able to span the gap up to 28 meter and support minimum of 30 ton vehicles loads. The bridge should be designed and constructed using advance materials and technology that are easily available. Therefore to fulfil the need, Carbon Fibre Reinforced Polymer (CFRP) and aluminium honeycomb material were selected as main materials for the bridge. CFRP layers will be produced by using carbon fibre SK-N300 tow sheets and epoxy resin SKRS as reinforcement and matrix respectively. Aluminium honeycomb was used as the core between CFRP layers to produce sandwiched structure in order to improve buckling resistance of top flange and web of beam, and consequently, reduce deflection.

Kosmatka (1999) has conducted structural testing of Composite army bridge (CAB) tread way. The tread way is capable of spanning gaps up to 12.2 m and able to support track and wheel vehicles up to MLC 70 (63,500 kg, 622 kN). The overall weight of tread way was calculated as 4763 kg. It is constructed using a carbon/epoxy substructure and a balsa core sandwich deck. Structural testing was conducted by applying total load of 311 kN that represents half of 70 ton M1A1 tank weight. The tread way failed at 334 kN load and that proof that the tread way is capable to support MLC 70.

Wight *et al*. (2006) presented development and testing of short span FRP bridge for Canadian Forces (CF) and international non-government organizations (NGOs). The bridge consists of two tread ways in form of tapered box beam. The beam prototype is constructed using GFRP pultruded sections that bonded together to form 4.8 m long and 1.2 m wide bridge. Height of beam is 0.5 m and 0.102 m at the mid and end span, respectively. The weight of the box beam is 500 kg. Field testing on the beam using a Bison vehicle (13,000 kg) has shown that the beam has sufficient stiffness and strength to support the load.

Xie (2007) has conducted three group of quasi-static test and performed finite element analysis to predict dynamic response of the full scale of box beam prototype as had been presented by Wight *et al*. (2006). The overall width and length of the box beam is 1.2 m and 9.6 m, respectively. Maximum height of beam at mid and end of span is 0.953 m and 0.102 m, respectively, and the total weight is approximately 1000 kg. The bridge was

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designed to support MLC 30 (27,000 kg). Testing results show that the beam structurally adequate for load of MLC 30. The work was continued by Landherr (2008) by performing quasi-static and dynamic testing under laboratory and fields testing of the beam. The tests show that the box beam can handle MLC 16 vehicles in dynamic testing.

Robinson *et al*. (2008) has developed and testing a short span FRC bridge with total length of 5.6 m, width of 0.76 m and thickness of 0.1 m. The bridge is design to be used as the bridge and others applications such as decking system, roadway matting, and also for overlaying of damaged bridge deck. The bridge was design to support load of MLC 30 and Palletized Load System (PLS) truck vehicles. Estimated weight of the bridge is 177 kg. It was shown that the bridge is capable of supporting load MLC 30 and PLS vehicles.

Generally, from previous research can be observed that maximum gaps that can be spanned by the composite bridges are 12.2 m and support load for MLC 70. Work by Agusril (2010), Agusril & Nor (2011), Agusril *et al*. (2012), and Nor *et al*. (2011, 2012) performed optimization design and simulation of a portable bridge that consists of two foldable beams using CFRP and Aluminium honeycomb as main materials. The overall length of each beam is 30 m and its width is 1.5 m. The beam consists of one centre section and two tapered sections with length of 10 m each which is connected using high strength steel joints. The height of centre beam is constant at 1 m, while the height of tapered beam varies from 1 m at joints to 0.1 m at the end of beam. Design and simulation using finite element analysis (FEA) software by simulating several CFRP sandwiched structure with various fibre orientation and aluminium honeycomb as the core, was performed. Result of simulations shows that the use of CFRP layers with proper fibre orientation and aluminium honeycomb thickness has successfully increased compressive, shear strength and reducing the vertical deflection at centre of beam. In order to validate the design and fabrication techniques used, a scaled down beam prototype is fabricated and tested.

MATERIALS AND METHODS

Portable Beam Prototype Design:

Scaling Down of Beam:

In order to produce the scaled down beam prototype; all of beam dimensions should be scaled down to 20%. Therefore, the total length of the beam will be 6000 mm, width 300 mm, and height of 200 mm as given in Figure 1.

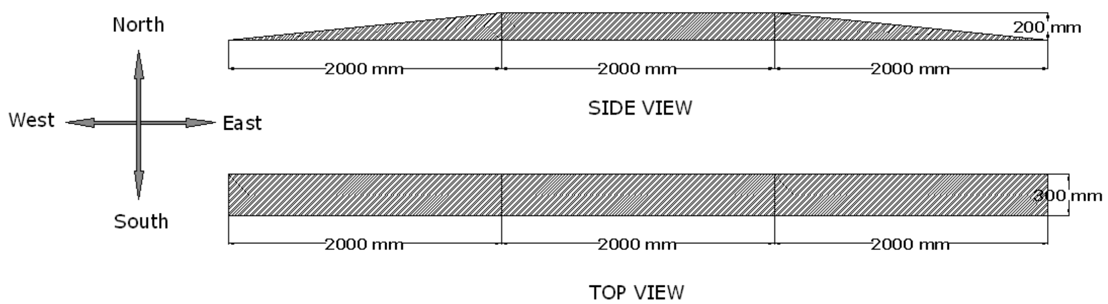

Fig. 1: Beam scaled-down prototype dimensions.

Thickness of top, bottom flange and web of beam should be scaled down as well by 20%. Thickness of one CFRP layer is constant, but number of layer should be reduced to the desired thickness. Type of aluminium honeycomb that being used is similar between scaled down and full scale beam prototype, but the thickness should be reduced to be 20%. The CFRP layers sequence and aluminium honeycomb thickness are given in Table 1, while the beam's cross-section that contains CFRP layers and aluminium honeycomb according to Table 1 is given in Figure 2.

Steel joints are designed to connect the beam sections that will allow the beam to be folded for storage and handling. However, the joints should have sufficient strength to transfer load from one section to the others. The actual joints dimension is produced by scaled down of proposed joints dimension by 20%. Design of joints was proposed earlier using high strength steel as shown in Figure 3, but for prototype construction purpose the joints have been redesigned as shown in Figure 4. Mild steel which is wrapped by CFRP layers material in order to maintain design strength was used to construct the joints.

Scaling Down of Load:

Portable bridge is initially design to carry load of minimum 60 ton or 600 kN. It means that one beam will support total load of 30,000 kg. For scaled down prototype loading calculation purpose, the actual load should be multiplied by $(20\%)^2$ or 0.04. This value is used to ensure that applied loading in the form of stress is similar

between full scaled and scaled down of beam prototype. This concept can be seen clearly in the following formulations:
Shear Stress, τ, = (Shear Force, V) / (Cross-sectional Area, A).
If A = depth x width, for full-scale prototype,
Then for 20% prototype A = 20% depth x 20% width = (depth x width) x $(20\%)^2$.
Thus, to achieve the same stress, τ, for full-scale and scaled down, the Shear Force, V, must also be multiplied by $(20\%)^2$, i.e.
Shear Stress, τ, = (Shear Force, V) $(20\%)^2$ / (Cross-sectional Area, A) $(20\%)^2$.
Consequently, the load to be applied on the 20% scaled down prototype must be multiplied by factor $(20\%)^2$. Therefore, design load for beam prototype will be 30,000 kg times 0.04 or equal to 1200 kg (12 kN).

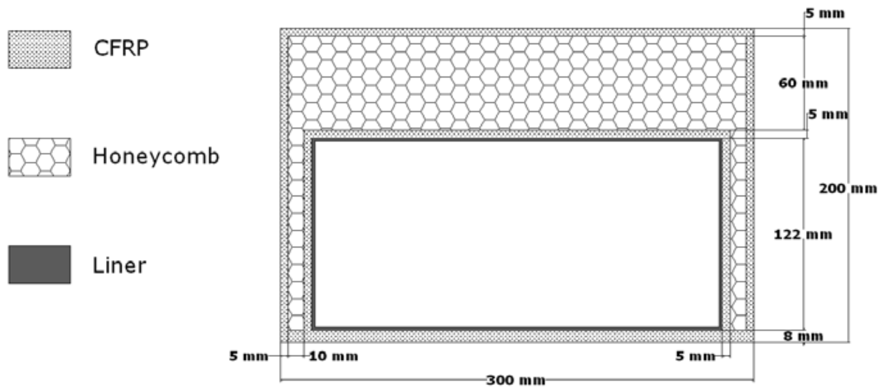

Fig. 2: Cross section of scaled down beam (Centre beam).

Table 1. CFRP layers sequence, orientation and core location in beam.

The part of structure	Sequence and orientation	Thickness (mm)	
		CFRP	Honeycomb
The top flange of tapered beam	$[90_1/0_2/90_1/0_2/\underline{core}]_s$	10	50
The bottom flange of tapered beam	$[90_1/0_2/90_1/0_1]_s$	8	0
The web of tapered beam	$[90_1/0_2/90_1/0_2/\underline{core}]_s$	10	30
The top flange of centre beam	$[90_1/0_2/90_1/0_2/\underline{core}]_s$	10	60
The bottom flange of centre beam	$[90_1/0_2/90_1/0_2]_s$	8	0
The web centre beam	$[90_1/0_2/90_1/0_2/\underline{core}]_s$	10	10

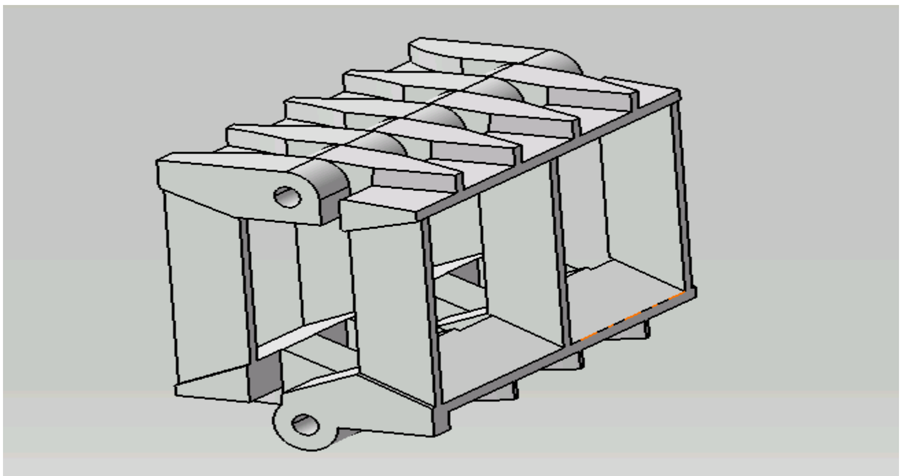

Fig. 3: The joints (AGUSRIL, 2010).

Portable Beam Fabrication:

Beam prototype was fabricated using wet hand lay-up method. Firstly, epoxy resin that consists of resin and hardener should be mixed properly by weight ratio 2:1 and carbon fiber sheet should be cut according to the need as presented in Figure 5a and 5b. The form was constructed using iron angle with dimension of 30 mm x 30 mm x 3 mm as the frame, while the liner cover using aluminium sheet with 1 mm thickness. The liner as shown in Figure 5b should be wipe clear to ensure no dust and other particles that can disturb the bonding of fiber sheets on the liner.

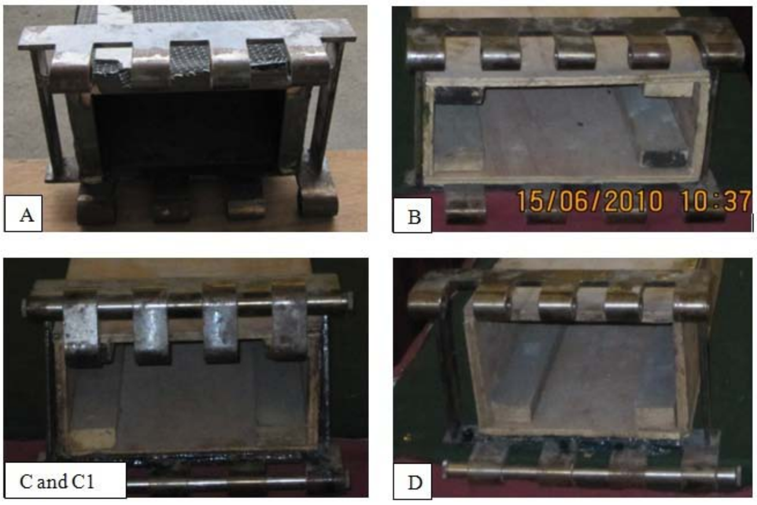

Fig. 4: The Actual joints for prototype.

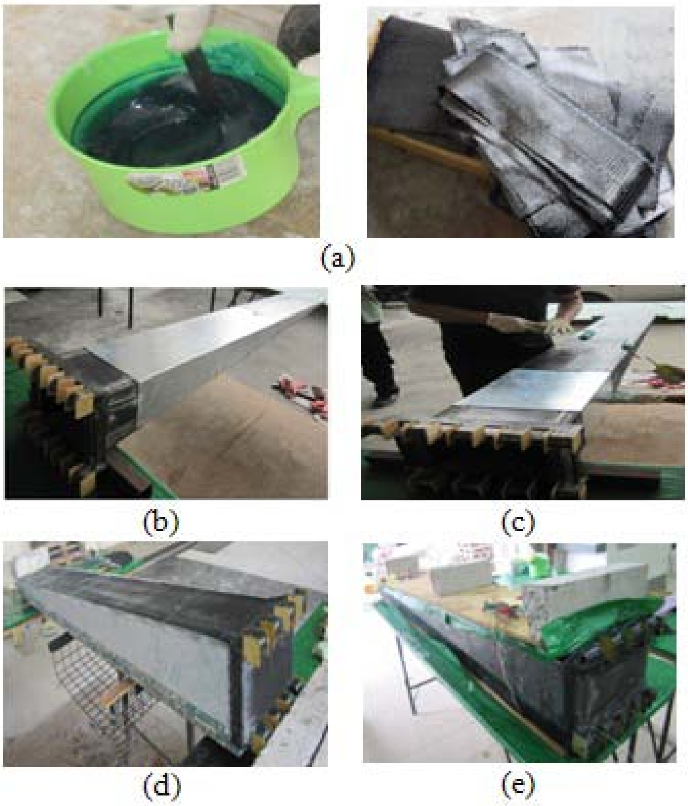

Fig. 5: Fabrication of beam prototype.

Apply the epoxy resin on the liner, then, immediately wrap the carbon fiber sheet on the liner and press them using roller to reduce any air void in fiber layer as shown in Figure 5c. Aluminium honeycomb can be attached in the beam as shown in Figure 5d and followed by continue applying carbon fiber sheets until desired laminate, as designed. The last step as shown in Figure 5e is attaching strain gauges on the beam and cover the beam using plastic sheet covered plywood and tie them together to ensure reasonable pressure is applied on the beam for final setting and to force out some trap air bubble and access epoxy within the laminate. Final weight of the tapered section and centre section are 37 kg and 44 kg, respectively. Therefore, total weight of the scaled-down 6 m beam is 118 kg. Full scaled of 30 m beam is predicted to be 5852 kg. Thus, the scaled-down prototype is only 2% of the actual full-scale bridge weight.

Structural Testing:

Load was applied using a 50-kN actuator attached on Magnus frame machine. Load was applied manually using hydraulic jack with load increment of 1 kN and the recording of strains and vertical deflections will be recorded using data logger. Testing was conducted by considering two types of loading, namely centric and eccentric loading. Centric loading means that the load centre equal to beam centre, while eccentric loading means that there is a space of 40 mm between loads centre to beam centre.

The load was distributed using six rods that represents the number of tank's wheels. There are 28 strain gauges and 6 displacement transducers were used to record strains and displacements of the beam due to the applied loads. The strain gauges and displacement transducer locations are given in Figure 6. The strain gauges and displacement transducer were connected to data logger.

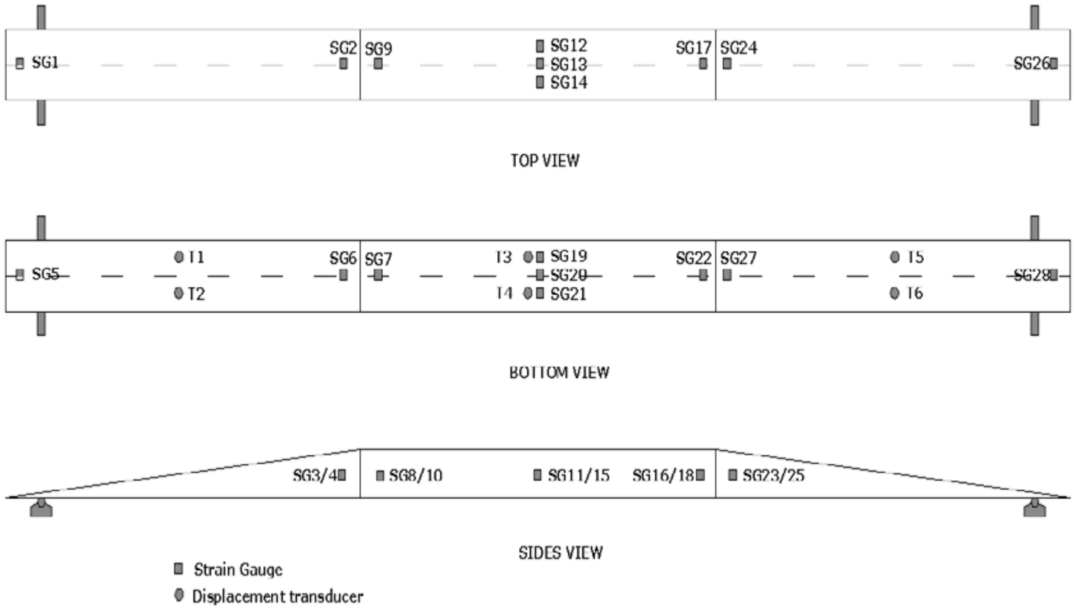

Fig. 6: Location of strain gauges and displacement transducer.

RESULTS AND DISCUSSION

Displacements:

The beam deflection at each load increment is given in Figure 7. In this figure can be seen that maximum deflection are 68 mm and 156 mm for maximum allowable and failure load, respectively. Actually deflections for military bridge are not limited directly by TDTC code, but must be considered when they cause any changes in loading, affect fit or alignment, or affect the use of equipment (TDTC, 2005). From this result can be concluded that actual maximum allowable load that can be supported by the beam is 11.3 kN that yield deflection of 68 mm about L/88. The deflection is lower than deflection limit of L/32 as stated by Robinson *et al*. (2008). The mid span deflection on each of loading increment is linear to load up to 11.3 kN and the pattern changed after that up to failure load of 12.9 kN. It was observed that beyond 11.3 kN, the load increases slowly while the deflection increased rapidly. The test was stopped at load of 12.9 kN due to excessive deflection. Eccentricity load effect can also be observed in Figure 7, where deflection of the mid span of beam at south side was bigger than north side due to the load pad for eccentricity load was placed at the south side. It can be concluded that maximum allowable load that can be supported by the beam is 11.3 kN. Therefore, it was predicted that full scale of the bridge prototype, with 2 beams, will be able to support vehicles load up to 47,000 kg (~MLC 50), including impact factor of 1.2.

Vertical displacement distribution is given in Figure 8. Six (6) displacement transducers are placed at station 1000, 3000, and 5000 as shown on the figure. Other displacement data were obtained by manually measure at station 0, 2000, 4000, and 6000 after the failure load recorded. It can be seen that there are differences between west and east deflection, i.e. deflection are -140 mm and -146 mm at station 2000 and 4000, respectively. It was clearly observed that the excessive rotation at top east joint has produced different deflection between west and east of beam. The condition can be observed clearly in Figure 9 and detail of west and east joints after failure are given in Figure 10.

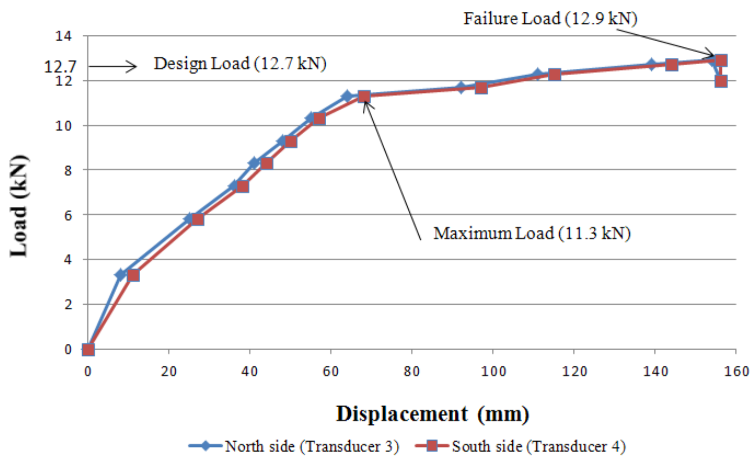

Fig. 7: Load versus displacement on the mid beam for eccentricity load.

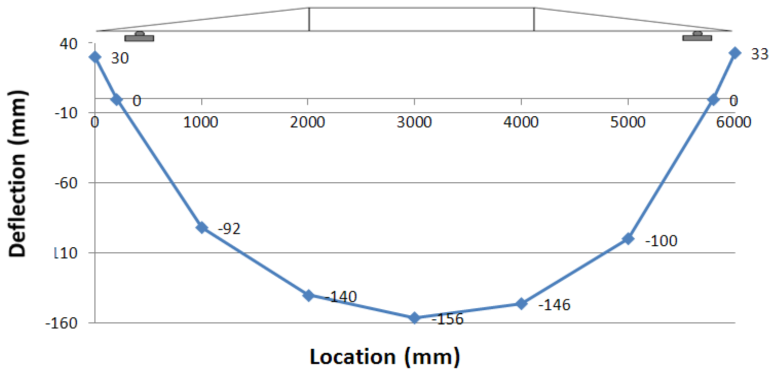

Fig. 8: Maximum vertical displacement distributions on beam due to eccentric load.

Fig. 9: Different deflections between west and east side of beam.

Strains:

Axial Compressive Strains:

During structural testing five strains gauges (*SG*17 is dead gauge) record the axial compressive strains as presented in Figure 11. It can be observed that top flange of beam experienced compressive axial strains with maximum compressive strains is -315 μs and -280μs for eccentric and centric load, respectively. The axial compressive strain due to eccentric loads is bigger than centric loads. Maximum compressive strain occurs at mid of centre beam at top flange as expected. The data were recorded using *SG* 13 that placed on centre line of mid span of beam.

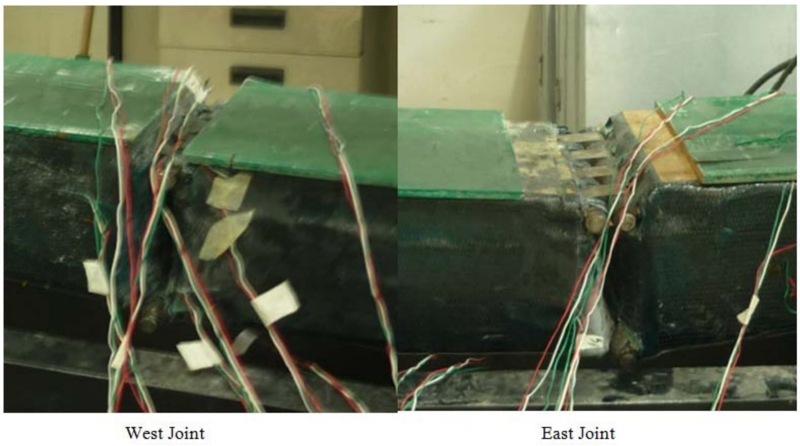

Fig. 10: Detail of west and east joints at failure load.

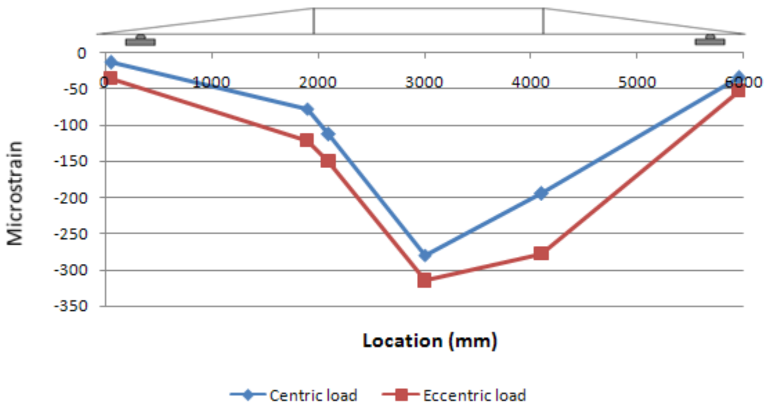

Fig. 11: Axial compressive strains distribution at top flange of beam.

Axial Tensile Strains:

The bottom flange of beam experienced axial tensile strains as given in Figure 12. In this figure can be seen that maximum axial tensile strains is 608μs and 556μs for eccentric and centric load, respectively. It can be observed that axial tensile strain due to eccentric loads is bigger than centric loads. For normal single span beam, maximum tensile strain is expected to occur at mid-span of centre beam. However, for the foldable beam, due to the design of the joint that cause moment rotation at joint centred at the top flange, thus creating longer lever-arm at joint toward the point of maximum tension, compared to at mid-span of beam. At mid-span of beam, moment rotation centred at the neutral axis of the cross-section. Maximum tensile strain occurs at the east joints of the beam. The data were recorded using *SG* 22 that placed on the left side of east joint.

Shear Strains:

Shear strains on beam's web due to centric and eccentric loads can be observed in Figure 13 and 14, respectively. *SG* 25 is a dead gauge that cannot provide shear strain data. From these figures can be observed that maximum shear strains occur at *SG*4 (north side of beam) with value of -461 μs and -359.5 μs for centric and eccentric loads, respectively. Shear strain due to centric load at this *SG* is bigger than eccentric load since the eccentric load was applied at opposite side of this *SG* (south side). Generally shear strain at *SG* 3, 8, 11, 16, and 23 due to eccentric load is bigger than centric load since the eccentric load was applied right above these strain gauges (at south side).
Insert Fig 14 here

Factor of Safety:

Factor of safety (FOS) for beam is obtained by dividing ultimate strain with max strain due to applied load on the beam. FOS for the beam is given in Table 2. From this table can be observed that minimum FOS is 17 that bigger than 1.5 as stated in Robinson *et al*. (2008). It was shown that the maximum strains of fibre in beam extremely lower than ultimate strain of fibre itself. Thus, the failure of beam is solely due to excessive rotation at east joint and produce excessive deflection.

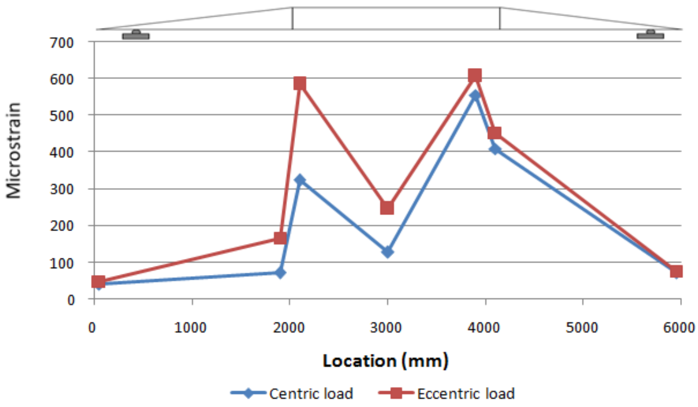

Fig. 12: Axial tensile strains distribution at bottom flange of beam.

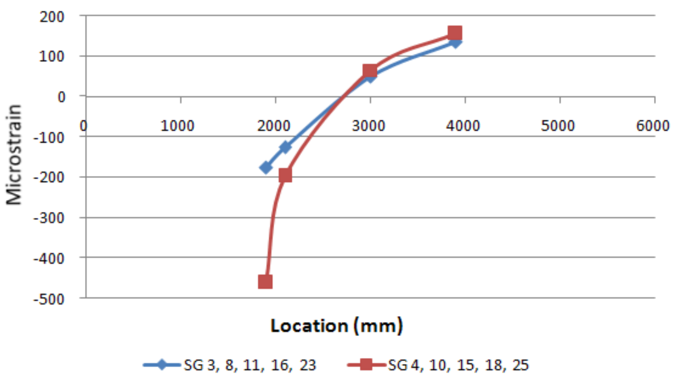

Fig. 13: Shear strains of beam’s vertical web due to centric loadings.

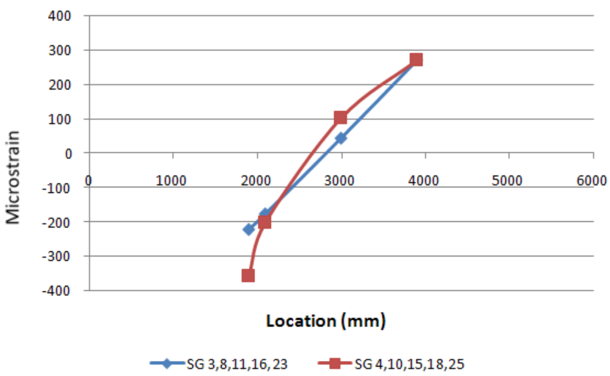

Fig. 14: Shear strains of beam’s vertical web due to eccentric loadings.

Table 2: Factor of Safety.

Location	Ultimate Strain (μs)	Max Strain (μs)	Factor of Safety (FOS)
Top flange (Compression)	-10600	-315	34
Bottom Flange (Tension)	10154	608	17
Webs (Shear)	15000	461	33

Conclusions:

Fabrication and testing of portable beam prototype has been conducted at Universiti Pertahanan Nasional Malaysia (UPNM). From the structural testing can be concluded that:

1. Maximum allowable load that can be supported by the prototype is 11.3 kN. This load is about 94% of the design load of 12 kN. However, the 12.9 kN failure load, declared due to excessive deflection, is about 1.08 times the design load.
2. Different strains and deflections between west and east side of beam occurred due to excessive rotation of east joint.
3. Generally, maximum axial compressive strains occur at top flange of centre beam that recorded by *SG* 13 (-315μs) while maximum axial tensile strains occur at left side of bottom east joint that recorded by *SG* 22 (608 μs) caused by eccentric loads. Maximum shear strain is -461 μs recorded by *SG* 4 due to applied centric load. From these situations can be concluded that strains on the beam are extremely low than ultimate strain of fibre that giving minimum factor of safety (FOS) 17 at bottom flange of beam. Therefore, it can be observed that fibre strength cannot be used optimally due to excessive deflection which is due to excessive rotation of joint in compression. Thus, the bridge could be improved by improving the design of the joint to avoid excessive rotation at top of joint. This could be done by replacing the hinge at the compression flange with male-female slot joint.
4. The overall calculated weight of the full scale beam is 5852 kg for total length of 30 m, while the overall weight of composite army bridge (CAB) tread way was calculated as 4763 kg for total length of 14.04 m. Therefore weight per length of the beam is 195 kg/m, while CAB tread way is 339 kg/m. It is calculated that the CFRP beam prototype is significantly lighter than the CAB tread way. However, performance of full-scale 30 meter foldable CFRP beam is yet to be fabricated and tested.

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Notations:

The following symbols are used in this paper:

CFRP	=	Carbon Fibre Reinforced Polymer
MLC	=	Military Load Class
SG	=	Strain Gauge
FOS	=	Factor of Safety
DTs	=	Displacement Transducers

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