VOL.39 Nº2 2022
https://doi.org/10.22491/IMECTA.10854.pt

Bridges and footbridges in pFRP: comparative study and analysis of assembly processes

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ABSTRACT: This paper presents the main information about the brazilian army's military bridges and the Pultruded Fiber Reinforced Polymer (pFRP) bridges developed around the world. Besides, presents the procedures for the assembly and static structural tests of a scaled model brazilian Glass Fiber Reinforced Polymer (GFRP) bridge, wich project has been made for support emmergency situations. Lastly, it compares some assembly aspects and resistance capacity between FRP and military bridges, indicating several advantages, especially regarding transportation and mounting in the field.

KEYWORDS: Bridges. Composites Materials. pFRP. FRP. GFRP. Structures.

RESUMO: O artigo reúne as principais informações a respeito das pontes desmontáveis existentes no Exército Brasileiro e das pontes em material compósito pultrudado de fibra e resina (pFRP) desenvolvidas ao redor do mundo. Além disso, apresenta os resultados obtidos na montagem e ensaio estático até a ruptura de uma ponte desmontável brasileira de fibra de vidro e resina (GFRP) concebida para o emprego em situações de emergência. Por fim, compara aspectos de montagem e capacidade de resistência das pontes em pFRP e as pontes tradicionais metálicas, indicando as vantagens logísticas de transporte e montagem no campo.

PALAVRAS-CHAVE: Pontes. Materiais Compósitos. pFRP. FRP. GFRP. Estruturas.

1. Introduction

Fiber-reinforced polymers (FRP) have two distinct phases: a fiber reinforcement structure and a polymer matrix. The fibers are usually carbon, aramid, or glass, while the polymer matrix is usually polyester, epoxy, phenolic, or vinyl ester [1].

There are several manufacturing processes for fiber-reinforced polymers, pultrusion being one of the most used processes due to its low cost and the possibility of obtaining profiles of varied cross-sections, with any lengths and with a high volumetric content of fibers in the longitudinal direction. FRP manufactured by the pultrusion process is often called pFRP (Pultruded Fiber Reinforced Polymer).

The tensile strength of pFRP is strongly influenced by the strength of the longitudinal fibers, while the shear strength is highly dependent on the matrix. In the pultrusion process, the fiber strands are embedded in the polymer matrix and pulled through a mold, acquiring the desired shape. Positioning the long fibers in the longitudinal direction gives pFRP the property of an orthotropic material.

It should be noted that FRP-type materials are already widely used in aeronautical engineering and in tubes and storage tanks in the oil and gas areas [2].

Interest in using FRP in civil engineering has increased in recent decades due to its physical and mechanical properties, such as high mechanical strength concerning low specific weight, high energy of impact absorption, corrosion immunity, and dimensional stability [1]. Such features make the use of these materials in dismountable bridges and footbridges attractive.

The main advantages of using FRP in dismountable bridges and footbridges are reduction of the weight of the structures, allowing reduced workforce costs for their assembly; ease of transport and installation, and the possibility of manufacturing specific profiles by different processes, such as molding and pultrusion [3].

Given the above and due to the innovative and recent nature of the use of FRP structural elements in the partial or total constitution of bridges and footbridges, this article aims to bring together the primary published studies with FRP profiles in the manufacture of bridge and footbridge structures of dual employment in Brazil and in the world. It presents in more detail the results of the project and the assembly of a dismountable bridge in glass fiber reinforced polymer (GFRP) carried out by the Military Institute of Engineering in partnership with the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering at the Federal University of Rio de Janeiro (COPPE/URFJ).

2. Military metal bridges used by the Brazilian Army

The Brazilian Army currently has four models of dismountable bridges. In addition to being designed for military operations, these structures have also been used to support Civil Defense in cases of public calamity where there is a need to re-establish access to affected locations or traffic on essential roads.

As they are made of steel or aluminum, these bridges are heavy, demanding a large workforce and specialized engineering equipment for assembly and disassembly, and the need for more robust transport logistics, with the use of trucks and vehicles designed for the transport of high loads.

The main characteristics of this equipment and information regarding transport and assembly are presented below.

2.1 M2 Bailey bridge [4]

The M2 panel bridge consists of a superstructure made up of standardized parts from the Bailey equipment, consisting of steel panels that, joined together, form trussed, double-supported longitudinal beams, transverse beams, and a steel and wood floor, among other items.

The material of the panels, transverse beams, and the floor is BS968 alloy steel, with a specific weight of 79 kN/m³. Each panel is 3.084 m long and 1.5 m high (Fig. 1), weighing 2.62 kN.

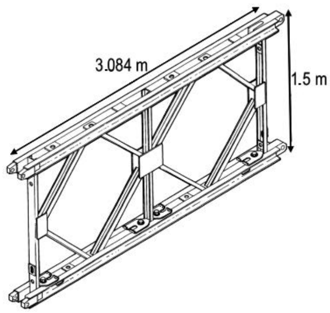

Fig. 1 – M2-type Bailey panel. **Source: [4].**

The Bailey bridge can be mounted with one or up to three rows of girders (simple-simple, double-simple, or triple-simple) on each side and up to three girder heights (triple-simple, triple-double, or triple-triple). The total width of the deck is 4.34 m, and the net width for vehicles is 3.81 m. Fig. 2 shows a 22 m long double-simple M2 Bailey bridge.

Fig. 2 – Double-simple Bailey bridge. **Source: [4].**

The maximum span possible using Bailey equipment is approximately 64 m in length for a 333 kN traffic load in the triple-simple configuration. In addition, a 25 m span in the double-simple structure supports a maximum traffic load of 1,120 kN.

Transporting the elements that make up the bridge, the tooling, and the support elements requires specialized engineering vehicles. Manual T5-275 [4] organizes all the materials for the bridge assembly in predetermined sets with volume and weight compatible with specialized transport vehicles. These are the so-called "load types," which vary according to the configuration and length of the bridge assembled. Fig. 3 shows a load-type transport scheme of bridge panels on the body of a dump truck.

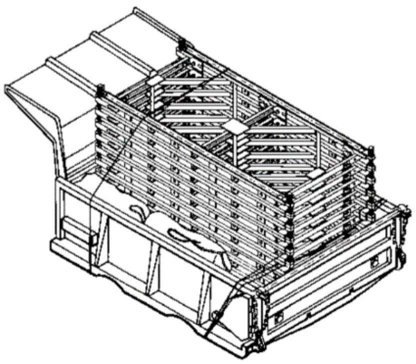

Fig. 3 – Load-type of panels on the body of a dump truck. **Source: [4].**

A simple-simple bridge with a length of 15.42 m has a self-weight of 209 kN, and the tooling elements, plus the constituent parts of the launching nose, have a total weight of 68 kN, requiring the transport of a whole load of 280 kN, approximately.

The bridge structure is mounted on steel rollers on one bank and manually pushed to the opposite bank. The bridge sections are assembled successively with the positioning of the panels, placement of the transverse beams, and installation of the horizontal and vertical bracings. After laying the bridge on the supports using hydraulic jacks, the floor is placed, and the access ramps are mounted.

The manual assembly of a simple-simple bridge of 15.42 m requires 33 people for 8 hours in total. Fig. 4 shows the bridge assembly scheme.

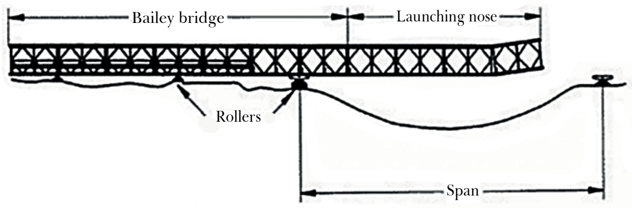

Fig. 4 – Longitudinal view of the bridge launched over the span. **Source: [4].**

2.2 M4T6 bridge [5]

The English-made M4T6 bridge consists of box-type beams and transversal beams in duralumin. The structure can be mounted on floating rubber supports, on intermediate aluminum stands, or double-supported on steel shoes.

In the latter configuration, the maximum span is 13.71 m long for up to a 390 kN traffic load, with a maximum support capacity of 1,127 kN for a span of 4.57 m.

Fig. 5 shows the component beams of the M4T6 bridge, and Fig. 6 shows a double-supported bridge during assembly.

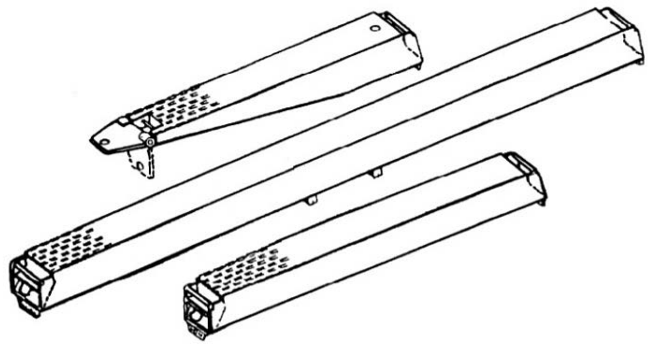

Fig. 5 – M4T6 bridge component beams. **Source: [5].**

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Fig. 6 – M4T6 bridge during assembly. **Source: Authors' collection.**

The transport of the constituent elements of the M4T6 bridge does not require specialized vehicles, and the load to be transported, including tooling, is 73.66 kN for constructing a bridge with 13.71 m in length, whose own weight is 54.72 kN.

The structure can be assembled only using simple tools or a crane to place it over the span. Fifteen people are needed to mount this bridge in a total time of 2 and a half hours.

2.3 Compact 200 bridge [6]

This bridge, of English manufacture, was acquired by the Brazilian Army in 1997 and was the evolution of the Bailey bridge project. The structural system is formed by panels connected by pins, forming longitudinal trussed beams on which the transverse beams and floor are supported, all made of steel.

The panels are BS 4360 galvanized steel, with a specific weight of 77 kN/m³. Each panel has a length of 3.084 m and a height of 2.22 m (Fig. 7), with a total weight of 4 kN.

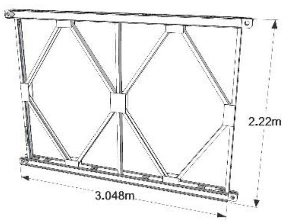

Fig. 7 – Compact 200 panel. **Source: [6].**

The Compact 200 bridge can be assembled in one to three rows of trussed girders (simple-simple, double-simple, or triple-simple) on each side of the deck, but with only one girder height. The total width of the bridge is 6.00 m, and the net width for vehicles is 4.20 m in the standard configurations and 5.30 m in the extra wide one, in which the length of the transverse beams is greater.

Despite being a temporary structure in the Brazilian Army, the bridge was designed for semi-permanent installation. Fig. 8 shows an 18 m long double-simple bridge.

Fig. 8 – Compact 200 double-simple bridge. **Source: [6].**

The maximum span that can be covered by the Compact 200 equipment is approximately 56 m for a 426 kN traffic load in the double-simple configuration. A 43 m span in the double-simple one supports a maximum traffic load of 1,043 kN.

Transporting the structure requires specialized vehicles, such as B-double trucks. Existing manuals do not provide a load-type system for organizing materials for transport, as in the Bailey bridge. Thus, transporting parts requires using practical experience.

A simple-simple bridge with a length of 15.42 m has a self-weight of 304 kN, and the tooling elements, plus the constituent parts of the launching nose, have a total weight of 107 kN, requiring the transport of a full load of approximately 411 kN.

The structure assembling is very similar to the Bailey bridge, with the limitation that only simple-

simple type bridges are manually assembled in emergency situations since the project predicts using cranes and tractors. The bridge sections are mounted successively with the positioning of the panels, placement of the transverse beams, and horizontal and vertical bracings. After laying the supports with hydraulic jacks, the floor is placed, and the access ramps are mounted.

Assembling a simple-simple bridge 15.42 m long requires a minimum of 100 people, with an estimated assembly time of 36 hours.

2.4 LSB bridge [7]

This bridge, of English manufacture, was acquired by the Brazilian Army in 2010 and was the evolution of the Compact 200 Bridge project, for military use, with ramps with adjustable inclination.

The structural steel system is formed by panels connected by pins, forming longitudinal trussed beams on which the transverse beams and the floor are supported.

The panels are BS 4360 galvanized steel, whose specific weight is 77 kN/m^3. Each panel has a length of 3.084 m and a height of 2.22 m, identical to the Compact 200 bridge (Fig. 7), with a total weight of 4 kN.

Assembling the structure only predicts using engineering equipment, such as cranes and tractors. It can be carried out in configurations with one to three lines of trussed girders (simple-simple, double-simple, or triple-simple) on each side, but with just one girder height.

The maximum span of the LSB equipment is approximately 56 m long for a 426 kN traffic load in the double-simple configuration. A 40 m span supports a maximum traffic load of 1,160 kN in the double-simple.

Transporting the structure, as with the Compact 200 bridge, requires using specialized vehicles, such as B-double trucks. Various load-type combinations can assemble the bridges according to their span and capacity.

Fig. 9 shows the material organized inside one of the trailers of the B-double truck for the simple-simple bridge assembly.

Fig. 9 – Material organized to assemble the simple-simple LSB bridge. **Source: [7].**

A simple-simple bridge that is 15.42 m long has a self-weight of 256 kN. The tooling elements, plus the components of the launching nose, have a total weight of 111 kN, and the articulated ramps have a weight of 186 kN, requiring the transport of a full load of approximately 553 kN.

Assembling a simple-simple bridge with a length of 15.42 m requires employing 36 people and cranes, with an estimated assembly time of 32 hours.

3. FRP bridges and footbridges

Below are some bridges made entirely or partially of FRP.

3.1 German GFRP bridge [8]

The University of Aachen, Germany, developed a 20 m long vehicular bridge for a 109 kN traffic load in five dismountable modules, with a net width of 2.75 m (Fig. 10).

The structure comprises two longitudinal truss beams linked together by cross beams. The structure elements are made of pGFRP profiles, including the floor. Connections are made with high-strength bolts and steel plates.

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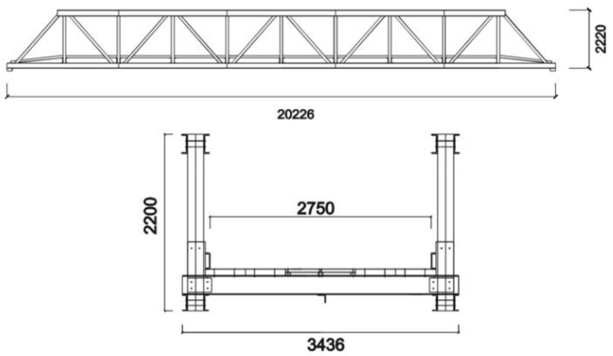

Fig. 10 – Longitudinal elevation and cross-section of the bridge (dimensions in mm). **Source: [8].**

As it is made of light material, an inexperienced workforce assembled the bridge on-site using simple tooling in three hours. The self-weight of the completed structure was 50 kN, and the breaking load was 350 kN, which occurred due to lateral buckling of the upper chord of the bridge truss.

Fig. 11 shows an MLC 12-type crossing the assembled structure. The bridge met the requirements of strength, deflection, and ease of transport and assembly in the project.

Fig. 11 – A vehicle during the field test. **Source: [8].**

3.2 Greek GFRP bridge [9]

A permanent road bridge, consisting of a deck supported on a pGFRP space truss with steel connections, was designed in this work developed by the University of Patras, Greece.

The structure was designed to cover a span of 11.6 m with a net width of the deck of 4.2 m, as shown in Fig. 12, for a traffic load up to 300 kN. The pGFRP structural elements have a square cross-section and were produced with S-type glass fibers and vinyl ester resin. The nodes were made of steel.

The total weight of the structure is127 kN, and it was transported to the assembly site on a truck. Its installation took two hours and required two cranes for positioning. Fig. 13 and Fig. 14 show, respectively, the structure being transported and positioned over the span.

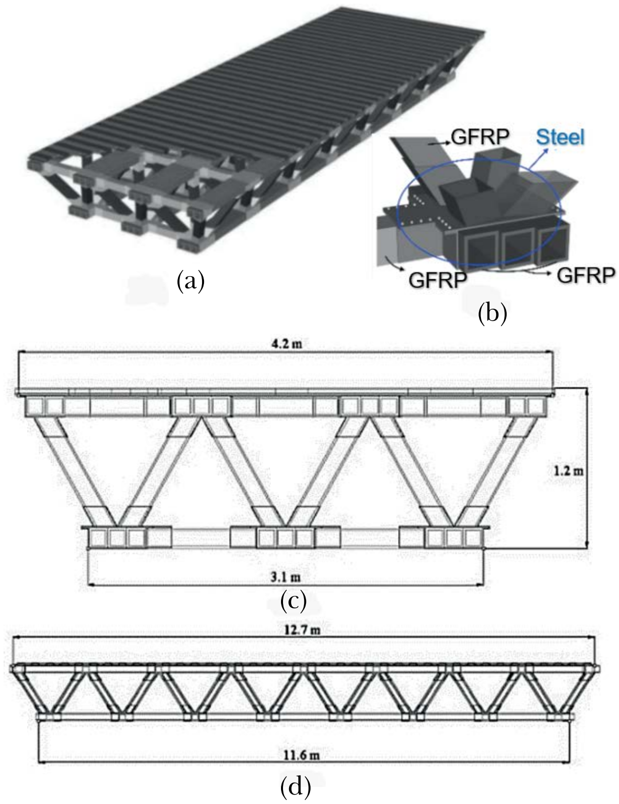

Fig. 12 – GFRP vehicular bridge: (a) general view, (b) detail of the steel nodes, (c) cross-section, and (d) longitudinal view. **Source: [9].**

Fig. 13 – Transport of the structure on a truck. **Source: [9].**

Fig. 14 – Installation of the bridge over the span with the aid of cranes. **Source: [9].**

3.3 American FRP military bridge [10]

The US Army developed a bridge to cover a four-meter span consisting of two independent roadways, each 76 cm wide, to provide the mobility of troops in combat or emergency situations, as shown in Fig. 15.

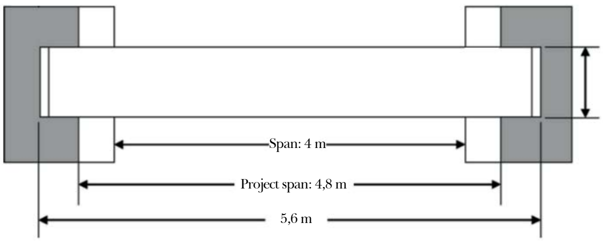

Fig. 15 – A roadway of the FRP military bridge. **Source: [10].**

The traffic load adopted for the project was 270 kN (MLC 30), determined from what the Trilateral Design and Test Codes for Military Bridging and Gap-crossing Equipment dictate [11].

The structure comprises glued square profiles, whose upper and lower faces are carbon fiber reinforced polymer (CFRP), and the other faces are GFRP (type E glass fiber and epoxy resin). Fig. 16 shows the cross-section of the roadway.

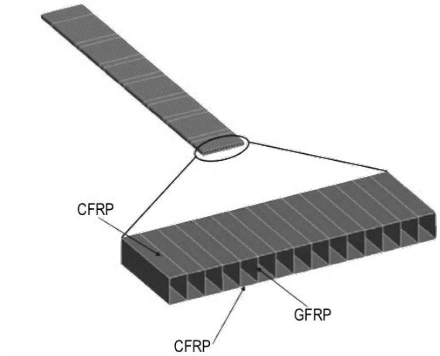

Fig. 16 – Cross-section of a roadway. **Source: [10].**

The bridge was manually positioned over the span without requiring specialized personnel. The weight of each roadway is 2.03 kN, for a total bridge weight of 4.06 kN. Fig. 17 shows an example of a vehicle crossing the bridge.

Fig. 17 – A vehicle crossing the bridge. **Source: [10].**

The authors concluded that using military bridges with this material is adequate for the rapid launch principles for small-span bridges.

3.4 Brazilian GFRP dismountable bridge [1;12;13]

A dismountable bridge in fiberglass composite material began to be developed in 2007 in partnership between the Brazilian Army and UFRJ to present an alternative to the military bridges used by the Brazilian Army in military operations and in support of Civil Defense.

The design of the GFRP dismountable bridge with a total width of four meters aimed to overcome a span of up to 30 m, supporting a vehicle of up to 280 kN. Fig. 18 presents the bridge's cross-section and the project beams' structural scheme.

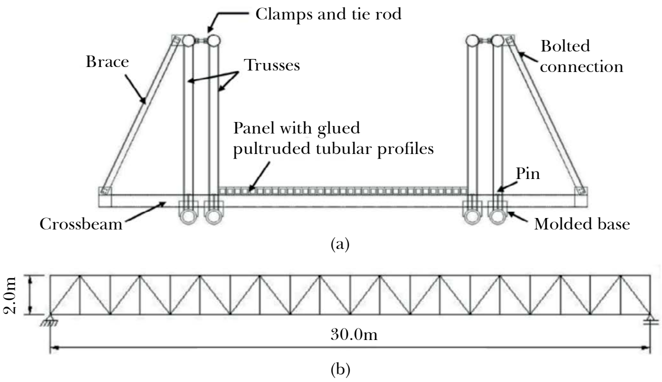

Fig. 18 – Dismountable Bridge: (a) cross-section, (b) structural scheme of the beams. **Source: [1].**

The structural system developed consists of:

- trussed beams composed of pultruded circular GFRP tubular profiles and metallic nodes, bonded by contact and pre-compressed using prestressed steel wires inside;
- crossbeams formed by two square tubular profiles glued together and supported on metallic nodes;
- lateral bracing of the trussed beams;
- horizontal bracing of the deck;
- floor with glued tubular pultruded profiles.

While the project was initially designed on a real scale, for the economic feasibility of testing the beams in the laboratory, a reduced model was developed in the scale 1:2.3 from the Theory of Similarity of Physical Models (TSMF) [14]. Thus, their results could be extrapolated to the prototype in actual size, reflecting the behavior of the full-size beams.

The choice of pre-compressed connections by contact occurred after conducting tests of connections between GFRP sheets with steel bolts subjected to double cutting. The authors verified that the strength of the sheets connected by bolts was much lower than that of the GFRP obtained in the mechanical characterization tests. The rupture occurred by tearing the sheet or contacting the hole in the bolt. Thus, they concluded that using bolted connections limits the resistant capacity of projects with composite materials. Therefore, this type of connection was discarded in the dismountable bridge project.

The design of the contact connection activated by the prestressing of steel wires arranged in the GFRP tubes was one of the innovations of this project, in addition to the detailing and manufacture of the metallic joints (nodes) for joining the GFRP parts and forming the truss system. , as shown in Fig. 19. Initially, the metallic nodes were made with welded steel tubes, resulting in high-weight parts with several imperfections. Subsequently, they were manufactured in aluminum, resulting in a lighter structure.

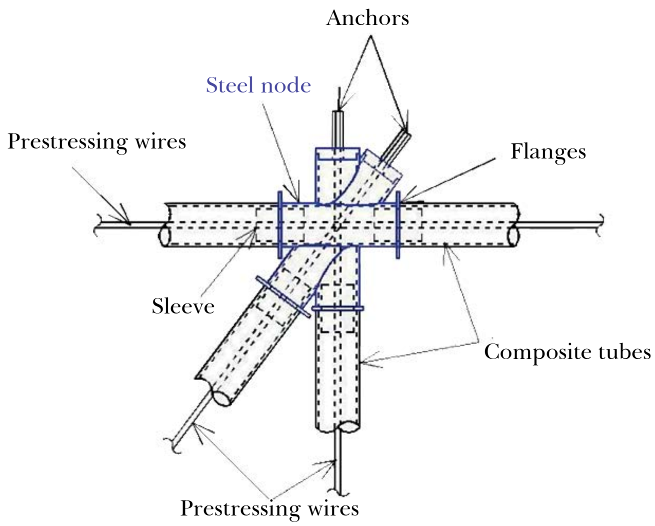

Fig. 19 – Tube-node detail of the trussed beam. **Source: [12].**

The pultruded profiles, injected grids, and prestressing wires were purchased in a single batch. The aluminum nodes were manufactured in 6351 aluminum alloy by the sand mold casting process in 2012, having received T6 type heat treatment (solubilization and aging) to increase its hardness. Fig. 20 shows a common node and central node of the lower chord and a common node and central node of the upper chord of the truss.

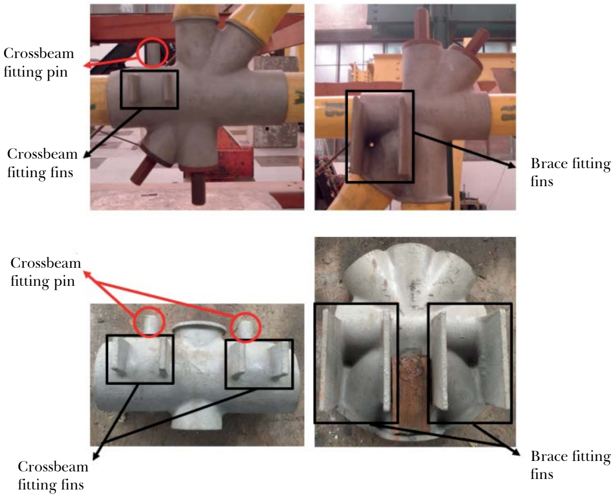

Fig. 20 – Aluminum nodes: (a) lower, (b) upper, (c) lower central, and (d) upper central. **Source: Prepared by the authors.**

The lower chord nodes were molded with a pin at the top to fit the crossbeams and two fins on the side to fix the crossbeams. The upper chord nodes have been molded with two fins to fit the brace.

The external reinforcement of the diagonals and uprights tubes was done by manual rolling, with the positioning of aluminum sleeves inside. At the same time, the upper and lower chord elements had their external reinforcement made by the internal stop of the aluminum nodes, while the internal one had aluminum sleeves, as shown in Fig. 21.

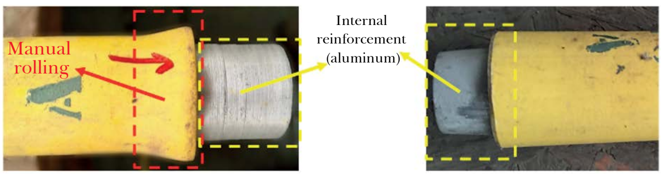

Fig. 21 – Reinforcements in GFRP elements: (a) uprights and diagonals and (b) upper and lower chords. **Source: Prepared by the authors.**

TSMF was applied only to composite tubes, while nodes and prestressing wires were adopted without respecting scale factors. While the nodes were designed only for the truss of the reduced model, these will be lighter in the prototype. The thickness of the parts of the reduced model was limited to the minimum thickness necessary for the casting.

The area of the GFRP tubes in the reduced model was distorted compared to the full-scale model (prototype). Thus, as the scale adopted in the reduced model was $k_l = 1/2.3$, the following scales were obtained:

- area of the profiles: $k_A = k_{13} = 1/(2.3)^3$;
- apparent specific weight: $k_{\gamma apparent} = 1/k_l = 2.3$;
- self-weight: $k_{pp} = k_{13} = 1/(2.3)^3$;
- applied mobile load: $k_F = k_{13} = 1/(2.3)^3$.

The experimental program developed in the study consisted of assembling one of the bridge beams with a total length of 13,06 m (equivalent to 30 m for the prototype, as per the adopted scale factor of 1:2.3).

Initially, steel nodes were used with reinforcement of steel jackets, steel sleeves, and composite sleeves at the nodes, as shown in Fig. 22.

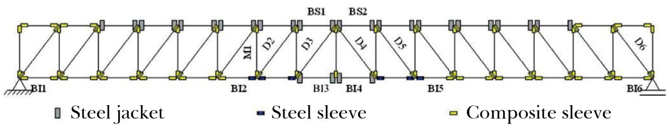

Fig. 22 – Connections adopted in the first tests. **Source: [12].**

The breaking load obtained in this test was 46 kN, equivalent to 560 kN of expected load on the prototype, according to TSMF [14]. The failure occurred by lateral buckling of the upper chord of the beam.

Subsequently, the steel nodes were replaced by aluminum ones with internal reinforcements made with aluminum sleeves in the pGFRP-node tube connections, as shown in Fig. 23.

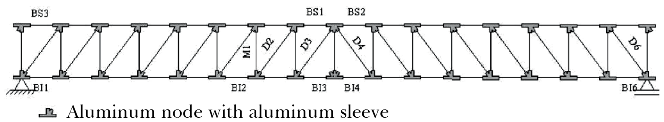

Fig. 23 – Connections adopted in the following tests. **Source: [12].**

With aluminum nodes, failure also occurred due to lateral buckling of the beam for a static load of 42 kN, equivalent to 511 kN of expected load for the prototype, according to TSMF [14].

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https://doi.org/10.22491/IMECTA.10854.pt

Despite providing a more flexible structure, aluminum alloy nodes still have advantages over steel ones. They are not subject to corrosion, are lighter, and facilitate the assembly of the truss beam by reducing weight and easily fitting the composite tubes. The aluminum alloy nodes are molded, significantly reducing defects during parts' manufacture [12].

In all tests, the loading system applied loads using tie rods attached in two nodes to the lower chord of the beams and connected to two hydraulic jacks that reacted to a reaction plate, as shown in Fig. 24.

The loading in the model does not have the same spatial distribution as the loading design of the bridge (three axes of load application, depending on the design vehicle). Furthermore, the behavior of the structure in service is linear. Therefore, the authors used the beam analogy to calculate the equivalent stiffness of a double-supported beam from the displacements obtained in the beam-truss loading test. They concluded that the load-bearing capacity of the beam-truss met the design and safety requirements required for the structure and that the design load moment (1,141.5 kN.m) was greater than the design requesting moment in the prototype (982.7 kN.m) [1]. Such implications made it possible to proceed to the complete bridge assembly project.

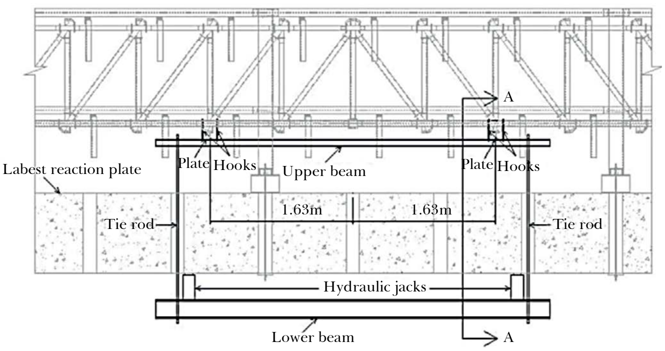

Fig. 24 – Sketch of the loading system adopted. **Source: [1].**

3.5 Canadian GFRP bridge [15]

The Canadian Army has developed a bridge for small spans for employment, both in military activities and natural disaster situations. This project sought to use light and cheap materials, which made it possible to transport and launch the structure with a minimum of personnel and specialized equipment.

The bridge is formed by two roadways in a box beam with variable inertia, with an inclination of 9.4° (Fig. 25). Each lane is 4.8 m long, 1.2 m wide, and 51.3 cm high at the center point. The structure was designed to support a 270 kN wheeled vehicle.

The beams were composed of square profiles and GFRP sheets (type E glass fiber and vinyl ester resin for the profiles, polyester resin for the lower and side sheets, and iso polyester resin for the upper sheet), all glued with high-resistance adhesive.

Each roadway weighed 2.5 kN, facilitating the transport and positioning of the structure over the span with no need for specialized personnel or equipment. Fig. 26 shows an example of a vehicle on the roadway.

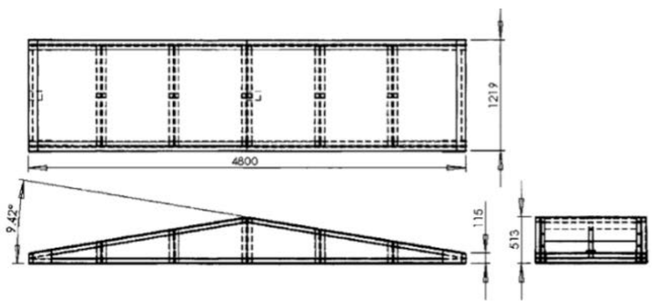

Fig. 25 – Top and elevation view of a roadway. **Source: [15].**

Fig. 26 – A vehicle on the roadway. Source: [15].

2.6 Chinese hybrid FRP/aluminum modular bridge [16]

The structure consists of two aluminum roadways supported on space trusses composed of aluminum elements, GFRP and HFRP (glass fiber reinforced polymer type E, carbon, and basalt).

The bridge was designed for a span of 12 m, a net width of 3.2 m (Fig. 27), and the capacity for a 100 kN traffic load specified in the Chinese General Code for Military Bridge Design [17].

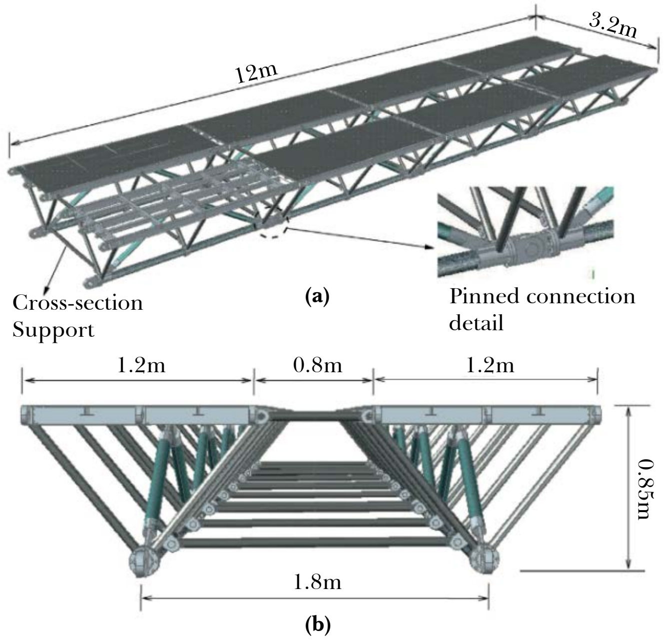

Fig. 27 – Hybrid modular bridge: (a) general view, (b) cross-section. **Source: [16].**

The connection of the bridge modules was made by aluminum pins while the metallic elements were welded. The fitting of the FRP and metallic elements was carried out by contact. Fig. 28 shows the details of connections similar to those used by Teixeira, Pfeil, and Batista [12]. The assembly of a roadway with four modules took 45 minutes, employing 12 people. The complete assembly took 90 minutes.

The total weight of the structure is 12 kN, enabling easy assembly. Its transport can be done in modules, not requiring huge vehicles and simplifying the transport logistics to the assembly sites.

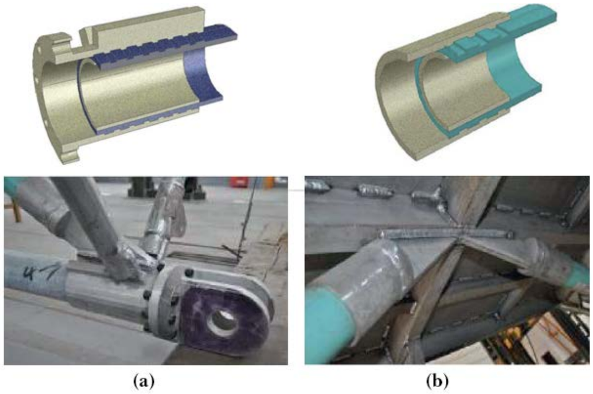

Fig. 28 – Sectional view of the connections: (a) HFRP, (b) GFRP. **Source: [16].**

3.7 Taiwanese GFRP temporary bridge [18]

Taiwan is a region with a high incidence of earthquakes and floods that eventually cause road bridges to collapse, resulting in traffic interruption. This scenario motivated the development of an emergency rescue bridge 10 m long and 3 m wide for a maximum traffic load of 50 kN.

The double-supported structure comprises longitudinal beams of pultruded GFRP I-profiles (pGFRP), connected using metal stiffeners and bolts and a GFRP grid floor. Fig. 29 shows the structure scheme.

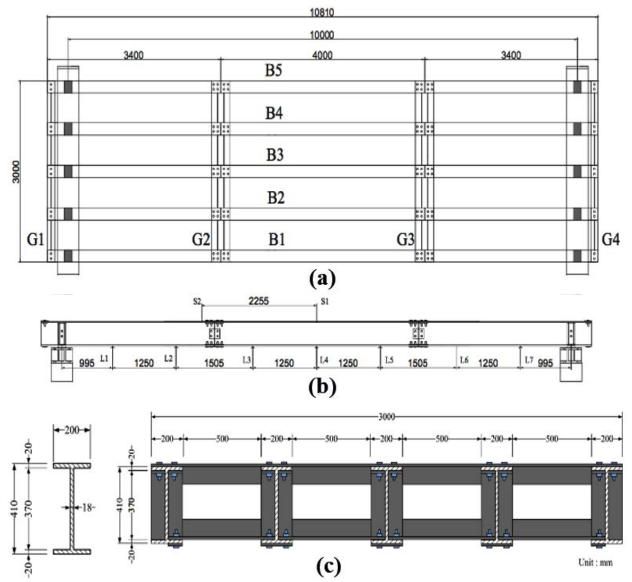

Fig. 29 – Temporary bridge: (a) top view, (b) longitudinal elevation. and (c) cross-section. **Source: [18].**

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Due to its low weight (29.42 kN), the structure was assembled by students, with the aid of simple tooling, in 10 hours.

Positioning of the structure over the span employed a small crane. The bridge met the design criteria with a high safety factor and resulted in a low self-weight structure, facilitating transport and assembly.

3.8 Taiwanese GFRP cable-stayed emergency bridge [19]

The bridge design uses the same deck system as the previous item, with the pGFRP span increasing to 20 m. Between the 10 m (steel) and 20 m (pGFRP) spans, a steel pillar was built from which the stays to support the deck came out, as shown in Fig. 30. The design traffic load was maintained at 50 kN.

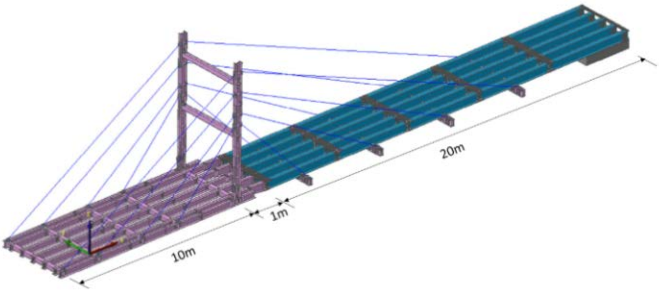

Fig. 30 – Cable-stayed bridge diagram with pGFRP in blue and steel elements in purple. **Source: [19].**

The suspended sections were assembled over the span with a counterweight to meet the emergency requirement in situations where it is not possible to access the other bank. Thirty people participated in the assembly, which took six hours, using simple tooling and a small crane. Fig. 31 shows a small truck crossing the bridge.

Fig. 31 – A vehicle crossing the cable-stayed bridge. **Source: [18].**

Considering the metallic elements, the total weight of the structure is 58.84 kN, allowing it to be easily transported by small trucks and considerably facilitating the assembly logistics.

4. Experimental study of the complete Brazilian GFRP dismountable bridge

With the results obtained by Teixeira [1] and Teixeira, Pfeil, and Batista [12,13], the work to develop the Brazilian GFRP dismountable bridge was continued.

Thus, a complete assembly of the reduced model of the bridge in the 1:2.3 scale was performed in the laboratory. The structure, 6.5 m long and 4.0 m wide, was assembled at COPPE/UFRJ's facilities by three people within 18 hours, using simple tooling and the aid of a hoist fixed to an overhead crane. This period was calculated according to the experience of the personnel involved in assembling structures of this nature. The period was increased by 3 times, considering the scale factor of 2.3. Unlike the structure presented in item 3.4 (Fig. 18), the assembled bridge had only one truss on each side of the deck.

The mechanical properties of the profiles used in this work are the same as those indicated in the Brazilian bridge's development in item 3.4. They can be found, in detail, in the publication in reference [1].

Fig. 32 shows the bridge's cross-section, a side view, and a top view detailing the horizontal and vertical bracing elements. In this figure, the floor was only shown in half the span in the elevation view to allow a better idea of the horizontal bracings.

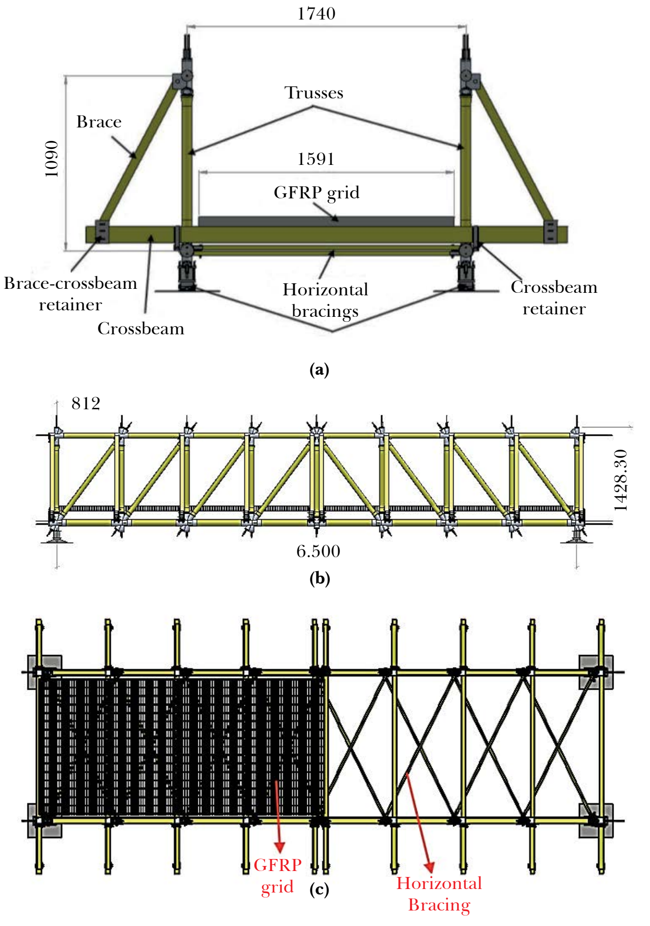

Fig. 32 – Dismountable bridge: (a) cross-section, (b) longitudinal elevation, and (c) top view (dimensions in mm). **Source: Prepared by the authors.**

One of the objectives of the assembly was to verify the idealized construction process, aiming at the application of prestressing and mounting the complete structure in the field.

The steps were as follows: assembly of the beams on the benches; prestressing of struts, diagonals, and upper chord; partial prestressing of the lower chord; lifting and laying the beams; installation of horizontal bracings; positioning of the transverse beams; installation of braces; positioning of the floor and final prestressing of the lower chord. Fig. 33 shows the bridge assembled.

Fig. 33 – Bridge of the reduced model assembled. **Source: Authors' collection.**

The analysis of the behavior of the structure concerning loads, deformations, and displacements during the assembly and loading phases used 54 sensors, divided into 33 electrical resistance strain gauges (ersg) with 5 mm in length, Kyowa brand, nine fleximeters with 100 mm stroke, Kyowa brand, and 12 load cells made from ersg. Fig. 34 shows the arrangement of sensors on the bridge.

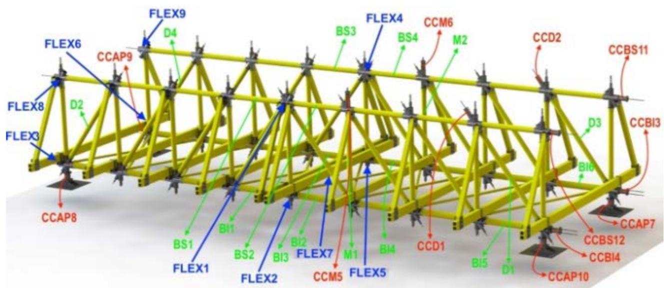

Fig. 34 – Bridge with all sensors. Source: **Prepared by the authors.**

The traffic load indicated by Teixeira [1] for the loading system was considered: the AV-LMU ASTROS II vehicle, whose total weight is 280 kN [20]. The same 1:2.3 scale

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was considered for the dimensions of the traffic load and its cargo, as per TSMF [14]. Fig. 35 shows the ASTROS vehicle and its main dimensions, and Fig. 36 represents the vehicle layout with reduced dimensions.

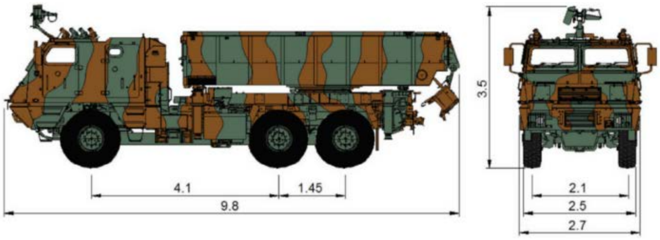

Fig. 35 – Dimensions of the ASTROS vehicle, in meters. **Source: [20].**

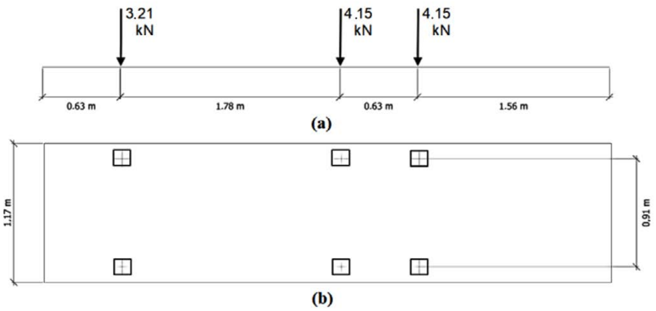

Fig. 36 – Vehicle layout and dimensions of the reduced model: (a) elevation view, (b) floor plan. **Source: Prepared by the authors.**

Once the vehicle's dimensions were known, a loading structure was manufactured in steel profiles that could simulate the vehicle's axles. Simulations were performed using the Solidworks Simulation tool, whose vertical displacements are shown in Fig. 37, to ensure that this structure would not deform with loading application. The displacements obtained were minimal, in the order of 0.45 mm for an applied load of 130 kN.

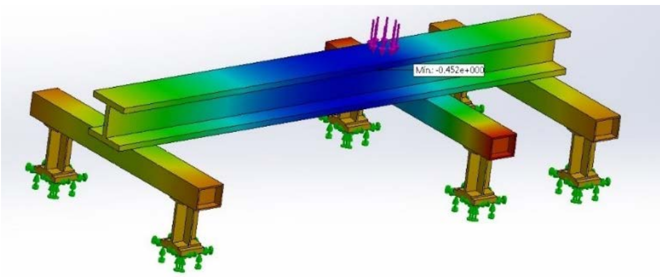

Fig. 37 – Numerical modeling of the loading structure with vertical displacements. **Source: Prepared by the authors.**

After fabrication, the loading structure was weighed with a load cell attached to the crane hoist, and a value of 9.48 kN was found. Fig. 38 shows the loading structure positioned on the bridge.

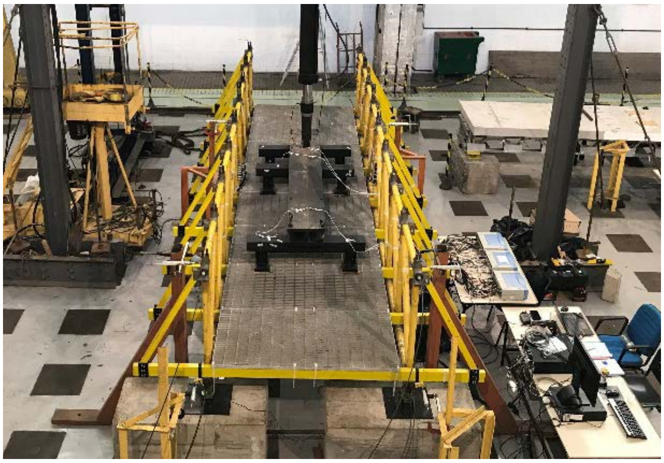

Fig. 38 – Loading structure positioned on the bridge. **Source: Authors' collection.**

The assembled bridge had its self-weight of 7.51 kN. Using the scale adopted in the project by Teixeira [1], the self-weight of the 15 m prototype can be estimated at 91.37 kN. This value is approximate, tending to be a little lower since the aluminum nodes had to maintain the thickness of the prototype nodes due to the casting process, despite being on a reduced scale, resulting in heavier pieces.

Static tests of the complete bridge were carried out to verify the behavior of the structure in service and at rupture. Due to the self-weight and the final prestressing, the average counter deflection measured at the mid-span of the beams was 21.04 mm. With the service load (11.50 kN) application, the average deflection in the center of the beams increased to 18.56 mm, corresponding to an average vertical deformation of 2.48 mm due to the applied load.

The bridge rupture occurred due to the lateral buckling of one of the beams, causing eccentric compression in the pGFRP element of the upper chord in the central span, causing its crushing. Fig. 39 shows the broken structure.

Fig. 39 – Top view of the bridge rupture. Source: **Authors' collection.**

The maximum load applied to the system was 97.62 kN. However, due to the TSMF [14], adding weight to the reduced model is required in such a way that it represents well the portion of the prototype's own weight. Thus, a total of 17.27 kN (2.3 times the self-weight of the reduced model bridge) was subtracted so that the maximum load considered was 80.35 kN.

The scale factor raised to the third power was considered, as predicted in the project by Teixeira [1], to estimate the maximum breaking load on the prototype bridge with a span of 13 m. Thus, the maximum load for the failure of the prototype bridge was estimated at 977.6 kN (80.35×2.3^3).

Eurocomp [21] considers the following resistance reduction coefficients for pultruded materials after complete curing and at temperatures below the softening temperature of the resin used: 1.39 for short-term load combinations and 3.54 for long-term load combinations. Then, the estimation of the bridge design load (maximum capacity) used the coefficient of 1.39, resulting in 703.3 kN.

5. Comparison between the FRP bridges presented and the metallic bridges used by the Brazilian Army

Table 1 presents an overview of the use of FRP materials in bridge structures and compares aspects of these structures with the metallic bridges used by the Brazilian Army.

The load values presented in Table 1 are for the failure of FRP bridges, as shown in items 3 and 4, and for the design of metallic bridges. For the Brazilian bridge, the maximum capacity was estimated by dividing the breaking load by 1.39, as already shown.

Table 1 – Comparison between the metallic bridges used by the Brazilian Army and the FRP bridges.

Bridge	Self-weight (kN)	Assembly (h)	No. of people	No. of people x hour
German	50	3	5	15
Greek	127	48	8	384
American	4	immediate	4	-
Brazilian (prototype)	91	40	6	240
Canadian	5	immediate	8	-
Chinese	12	1.5	12	18
Taiwanese (2015)	29	10	10	100
Taiwanese (2016)	59	6	30	180
M2 Bailey Bridge	209	8	33	264
M4T6 Bridge	55	2.5	15	37.5
Compact 200 Bridge	304	36	100	3600
LSB Bridge	256	32	36	1152
Bridge	**Span (m)**	**Breaking Load (kN)**	**Design Load (kN)**	
German	20.00	350	109	
Greek	11.60	-	300	
American	4.80	-	270	
Brazilian (prototype)	13.00	978	703	
Canadian	4.00	330	270	
Chinese	12.00	-	100	
Taiwanese (2015)	10.00	200	50	
Taiwanese (2016)	20.00	-	50	
M2 Bailey Bridge	15.42	-	510	
M4T6 Bridge	13.71	-	390	
Compact 200 Bridge	15.42	-	570	
LSB Bridge	15.42	-	570	

Source: Prepared by the authors.

The first analysis concerns the self-weight of the assembled structures.

Compared to the simple-simple Bailey bridge with a span of 15,42 m, the Brazilian bridge has 43.72% of its self-weight, while for the Compact 200 and LSB bridges, this proportion drops to 30.10% and 35.70%, respectively.

The self-weight of the Brazilian bridge is 67% greater than that of the M4T6 bridge. However, the maximum capacity of this bridge is 390 kN, corresponding to 55% of the maximum capacity of the Brazilian bridge.

Despite having their self-weights of the assembled structures and the structural scheme adopted, the other studies showed that the assembly procedures were simple, with the need for a small workforce for a reduced assembly time.

The number of people needed to assemble the bridges is a variable that depends on the structure's self-weight, the equipment and tools available, and the assembly process itself. However, the data obtained indicate (from the point of view of the self-weight) that pFRP bridges demand less workforce than the metallic bridges used by the Brazilian Army and, consequently, shorter assembly time.

The analysis of product No. of people × hour (Table 1) shows that assembling the Brazilian bridge is much faster than the Bailey, Compact 200, and LSB bridges if considering the same number of people for the task.

This same comparison with the other pFRP bridges indicates that the Brazilian bridge requires more time than most bridges in FRP. This occurs as this is the only one requiring prestressing in the constituent elements of the beams in the assembly process. This step must be done with great care since prestressing different from those established in the project will directly influence the structure's support capacity.

Another conclusion is that increasing the number of personnel for the assembly may reduce the time required for the Brazilian bridge.

Finally, when comparing the support capacities, the Bailey bridge apparently has 72.5% of the support capacity of the Brazilian GFRP bridge, while the M4T6 bridge, 55.5%, and the Compact 200 and LSB, about 81.0%.

6. Conclusions

This study presented the metallic military bridges used by the Brazilian Army, not only in military operations but also in support activities for Civil Defense in cases of public calamity.

Furthermore, this study presented other works using pFRP materials in global bridge projects. They demonstrated the feasibility of using these materials concerning strength and ease of transport and assembly.

A GFRP (glass fiber and polyester resin) bridge was tested by the Brazilian Army in partnership with UFJR. The complete structure was assembled in a reduced model 6,5 m long on a 1:2.3 scale, and the static loading test was carried out to verify its behavior in service and at rupture. This assembly led to the following conclusions:

- the bridge did not require specialized personnel and equipment for its assembly;
- due to the low weight of the elements that make up the structure, compared to those of traditional construction materials, the launch time proved to be quite efficient, considering that it was carried out by only two people;
- assembly from completely disassembled elements reduces the volumes to be transported, requiring fewer specialized vehicles for transport;
- the prestressing procedures of the beam elements indicated that they were suitable for execution in the field;
- the breaking load of the structure was 8 times higher than the design load;
- the failure occurred as expected, with the transverse displacement of the upper node of the beam, and
- compared to metal bridges currently used by the Brazilian Army, the pFRP dismountable bridge can enhance support in public disasters or combat situations.

Below are some suggestions resulting from the verifications carried out in this study and to continue the study of a dismountable bridge in composite material:

- modify the brace design, removing their connection with the crossbeams, or stiffen them sufficiently to increase the efficiency of the vertical bracing;
- manufacture a vehicle with the geometry of ASTROS to better simulate the distribution of loads on the bridge;
- evaluate the dynamic behavior of the structure, and
- check the physical and mechanical properties of the project profiles under temperatures above 60°C.

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