Structural behavior of open truss FRP bridge without side support

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Abstract. Lightweight makes the advantage of Fiber Reinforced Polymer (FRP) as one of the choices of truss bridge without side support materials. The simple shape of the structure and bridge connection system is believed to be the reason the bridge with this type of structure can use in emergencies that require rapid mobilization and installation. However, with the limited choice of FRP structural element profiles available, combined profile preparation was carried out in the structure to be used as a truss bridge structure profile. This paper describes the structural response identification of the use of a combined profile as seen from static and dynamic load testing of a full-scale bridge structure with a 16-meter span that planned to use as a pedestrian and light vehicle bridge. The load is applied in stages to be able to observe changes in the response of the structure and connection system. The results show that the bridge without side support has a load-bearing capacity that is strongly influenced by the stability of the compressive members and connection systems, which is very visible in the dynamic characteristics of the bridge in the lateral direction which is quite far when compared with the tests in other references.

1. Introduction

Emergency bridges are an essential part of maintaining mobility and logistics connectivity in the event of a disaster. The latest preparation of Bailey steel bridge emergency bridge-type by the Directorate General of Highways was carried out in 2018 and 2019 to meet the priority needs of disaster management in 22 areas of the national road implementing offices in Indonesia. That preparation shows that there is a significant need to prepare an emergency bridge used to serve light operational disaster relief vehicles, which can be transported quickly without the need for heavy equipment during installation in remote areas, and which can be done by workers without high skills [1].

Based on these needs to be able to increase the speed of installation and long-term performance of emergency bridges, the Institute of Road Engineering was trying to develop a bridge structure made from Fiber-Reinforced Polymer (FRP). The application of composite materials such as FRP has considerable potential in developing bridge structures. FRP has suitable physical and mechanical properties, such as the ratio of strength to weight, high strength and stiffness, high impact strength, non-magnetic and non-thermal conductive properties, as well as high resistance to corrosion and chemicals [2]. It can also be an effective solution with the life cycle of a structure to reduced installation and maintenance costs for corrosion and chemicals [4]. Increasing mass production as applied to the aircraft industry can anticipate high initial production costs and uncertain long-term costs such as maintenance to protect against fire, and dismantling and disposal of FRP materials [6]. The flexibility of the direction of installation of the fiber to accommodate the main force planned to bear is one of the economic benefits of using FRP elements [6].
The development of bridges made from FRP in Indonesia can follow what the USA develop for pedestrian and light vehicles bridges since the late 1980s [7]. Better and more comprehensive knowledge about the fundamental properties of the composite, and their long service life [2] related to the complex structural behavior that is strongly influenced by composite materials and jointing methods [3] can obtain through that development. Things to note are that the main ingredient of FRP elements, especially glass fibers, experience deterioration due to increased temperatures, especially if burdened with compression and shear [8] and also due to UV radiation for more than 3000 hours [9] which very decisive in a tropical country like Indonesia.

Research and development of bridges made from FRP in Indonesia began in 2013 has produced two prototype bridge frames for pedestrians and light traffic respectively in 2016 and 2019. FRP profiles formed by the pultruded method, which is estimated to be a cost-effective composite manufacturing technique [3], can use for the development of this bridge in the future. The limited FRP pultruded profile which produces for the structure of building roofing in Indonesia, applies as bridge truss structure elements with some modification.

The study began by identifying the physical and mechanical parameters of the pultruded FRP material made from glass, which showed a significant effect of aging testing and an increase in temperature on changes in mechanical properties [10]. The research continued by making a test model truss system in 2014, and a prototype of an FRP pony-truss Warren-type bridge with side support in 2015-2016 using two closed C channel pultruded-FRP-profiles combined into a box-like profile (Figure 1). The results obtained from these tests show that there was a failure in the connection area between the joint profile and the steel plate used to connect the FRP pultruded profile frame.

![Figure 1. Prototype pony-truss Warren-type 8 meters span bridge with side support in 2016 using a combined of closed two closed C channel pultruded-FRP-profiles](image1.jpg)

![Figure 2. Views and parts of the 16 meters span FRP bridge](image2.jpg)
Based on this, finally, in 2019, the purpose of this study is to determine the structural performance of the FRP bridge prototype development result. A pony-truss FRP bridge prototype was developed to identify the structural response using the same FRP pultruded combined profiles. Static and dynamic load testing carried out on a full-scale bridge structure that planned to utilize as a pedestrian bridge and an emergency light vehicle.

The bridge prototype is a truss bridge with 16 meters long and 2.5 meters wide which has a length of 2 times that of the 2016 test bridge (Figure 1). The frame uses a combined two open C channel pultruded- FRP-profile with a depth of 150 mm and a thickness of 7 mm (Figure 3) combined with bolts and gusset plates and coupling plates in the center of each compression chord to minimize the occurrence of buckling [10].

2. Experimental and numerical model
The FRP bridge prototype that studied is a bridge system of Pratt type form pony-truss without using side support on vertical trunks as is commonly applied to be the choice in the design of pedestrian bridges and light vehicles [1] because of its simple shape [12]. The truss bridge also has high resistance in the longitudinal direction but low resistance to shear [1].

The bridge consists of two main components; namely, the truss system rests on two trusses and the floor system. The truss system consists of a compressed member, tension member, and a diagonal member, the flexible floor beam being a buffer to provide stability [13]. Stringers and floor beam supported the deck system where the type of pony-truss type bridge structure like this is one of three types of structural systems developed into pedestrian bridges in the USA [7].

One of the planning criteria for pultruded FRP bridges in the form of pony-truss in 2019 refers to the "Guide Specifications for Design of FRP Pedestrian Bridges, AASHTO 2008". The planned load is pedestrian load of 3 kPa. The bridge also allows light vehicles to be able to cross in emergencies such as ambulances or other logistical transport vehicles so that it is assumed to be 5 tons, and the wind load for the open frame bridge system is 1.68 kPa. The conditions that must be fulfilled are deflection not exceeding 1/200 span length, fundamental vertical frequency not less than 5 Hz and lateral frequency fundamental not less than 3 Hz.

2.1. FRP pedestrian bridge prototype
Testing performed on a prototype FRP bridge with a width of 16 meters, and a width of 2.5 meters, where the span range is an effective span for FRP truss bridges that range from 9 meters to 30 meters with a width of between 1.5 meters and 3 meters [7] as shown in Error! Reference source not found.

2.2. Member profiles, deck and connections
The profile used for the truss component was C channel profile 150.65.20, with a profile thickness of 7 mm, and the deck system uses a 50 mm pultruded grating as shown in Figure 3 dan Figure 4. The estimated total weight of the truss bridge reaches approximately 5 tons including bridge truss elements, connection systems, and pultruded grating for bridge deck systems. Details of truss elements weight are shown below.

![Figure 3. A combined two open C channel pultruded-FRP-profile](image)
At the connection, the bridge test model uses ASTM A325 16 mm diameter bolts and 10 mm thick gusset plates and addition, the coupling plate stiffener is connected to shorten the buckling length and bind bridge chord compression members as shown in Figure 5.

2.3. FRP material characteristics

The composition of the content of heterogeneous FRP constituent materials makes FRP elements anisotropic and brittle [6] will affect the design process of FRP elements or connection systems [3]. The mechanical properties of PFRP materials must be tested beforehand because of the fiber composition and stiffness that varies from manufacturer to manufacturer [14], which shows a significant difference compared to the American Society of Civil Engineers reference, 2010. Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures especially in the minimum thickness and shear strength requirements that seen in Table 2 [10].

### Table 1. Bridge truss element

| No. | Element       | Number of Element | Length (m) | Volume (m³) | Weight (kg) | ∑ Weight (kg) |
|-----|---------------|-------------------|------------|-------------|-------------|---------------|
| 1   | Top Chord 1   | 12                | 1.890      | 0.007659    | 13.786      | 165.434       |
| 2   | Top Chord 2   | 8                 | 1.890      | 0.007659    | 13.786      | 110.290       |
| 3   | Top Chord 3   | 16                | 1.890      | 0.007659    | 13.786      | 220.579       |
| 4   | Diagonal Chord 1 | 8              | 2.395      | 0.009713    | 17.483      | 139.867       |
| 5   | Diagonal Chord 2 | 12              | 2.443      | 0.009713    | 17.483      | 209.801       |
| 6   | Floor Beam    | 30                | 1.800      | 0.007293    | 13.127      | 393.822       |
| 7   | Stringer      | 11                | 2.320      | 0.009365    | 16.857      | 185.427       |
| 8   | Vertical Chord 01 | 4              | 1.800      | 0.007293    | 13.127      | 52.510        |
| 9   | Vertical Chord 02 | 14              | 1.800      | 0.007293    | 13.127      | 183.784       |

**Specific Gravity = 1800 kg/m³**

Total Chord Weight (kg) 1,662
Table 2. The minimum FRP characteristics based on ASCE 2010 and 2013 test results [14]

|                        | ASCE 2010 | Fiber-beam (FRP) |
|------------------------|-----------|------------------|
| Fiber type             | Min. E-glass | E-glass         |
| Minimum thickness/element | Min 9.6 mm | 7 mm             |
| Tensile strength       | 207 Mpa   | 370.4 ± 18.5 MPa |
| Compressive strength   | 207 Mpa   | 115 ± 12.9 MPa   |
| Flexural strength      | 207 Mpa   | 498.0 ± 42.1 MPa |
| Shear strength         | 31 MPa    | 40.3 ± 7.7 MPa   |
| Modulus of elasticity  | 20684 MPa | 20600 MPa        |

2.4. Numerical model

A numerical model created to verify the results of the response test. FRP bridge behavior is simulated with structural analysis software with fundamental frequency as a reference. At this stage, trial and error are carried out on the modulus of elasticity to obtain the same fundamental frequency.

3. Test setup

Identification of the structural response characteristics carried out with dynamic and static testing of the FRP bridge prototype. The things observed in the FRP bridge prototype performance test include the visual condition of the elements and structure of the bridge, the strain on the chord, structural deformation, and the natural frequency of the bridge structure. Dynamic tests carried out in the vertical and lateral directions of the test model. The vertical structural response obtained by passing people walking and running on the bridge. The transversal response obtained by giving a boost to the frame with the help of human force. The sensor used is an accelerometer placed in the middle of the span (Figure 6). The direction of the accelerometer is positioned according to the testing requirements, namely vertically and transversely of the bridge.

Static tests are carried out by overloading the bridge with a maximum load of planned 12 tons. At each load increase, a visual inspection conducted to observe changes in the bridge behavior. In addition to visual observations, strain measurements and deformations are also carried out. Strain measurement using strain gauge is mounted on top and bottom chord, while deformation measurement uses Total Station with a point of view on each gusset plate. The instrumentation performance test layout of the FRP bridge prototype shown in Figure 6 and Figure 7. Complete loading order and weight on each segment presented in Table 3 which indicated in I, II, III, and IV number for each load increment. Loading segment numbering indicated by two joints individual connected one span.

4. Test result

4.1. Dynamic test

Dynamic test results on a natural vertical frequency were 8.06 Hz for people walking and 7.39 Hz for people running. Meanwhile, the natural frequency of the lateral direction is 1.46 Hz, which means it is still lower than the AASHTO regulation, which is not less than 3 Hz.

4.2. Static test

In static testing, the FRP bridge test model has collapsed close to loading 9 tons. Test visualization from the beginning to bridge collapse seen in Figure 8.

Error! Reference source not found. shows the results of deflection measurements on the FRP bridge prototype. The maximum deflection measured at 9 tons load is 15.83 mm measured by the Total Station and the deflectometer calibrated before testing. Meanwhile, Error! Reference source not found. is a strain sensor recording on the lower and upper FRP members installed in the middle of the range where negative value indicated compression stress, and the positive value indicated tension stress.
Measurement in vertical deflection and lateral deformation of the top chord also carried out. Figure 9 shows the change in the position of the top chord towards the inside of the bridge until it loads 6 tons.

![Figure 6. Instrumentation layout for bridge loading](image)

![Figure 7. Typical instrumentation attached in gusset plate](image)

Table 3. Planned sequence load in each span

| Span indication | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | Total load (ton) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|------------------|
| Load I          | -   | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | -   | -   | 3.0              |
| Load II         | -   | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | -   | -   | 6.0              |
| Load III        | -   | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | -   | -   | 9.0              |
| Load IV         | -   | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | -   | -   | 12.0             |

Table 4. Displacement of FRP bridge prototypes at each point static test

| Load Combination | 1 (mm) | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|------------------|--------|---|---|---|---|---|---|---|---|
| Load I           | -0.90  | -3.40 | -4.60 | -5.80 | -6.30 | -5.60 | -4.70 | -3.90 | -0.70 |
| Load II          | -0.90  | -5.10 | -8.10 | -10.10 | -11.20 | -10.40 | -8.30 | -5.50 | -0.20 |
| Load III         | -      | -   | -   | -   | -15.83 | -   | -   | -   | -   |

* Displacement Loads I and II are obtained from Total Station measurements

* Displacement Load III is obtained from the deflectometer sensor just before prototype collapse

Table 5. Strain of the FRP bridge prototype during static testing

| Load Combination | Bot 01 | Bot 02 | Top 01 | Top 02 |
|------------------|--------|--------|--------|--------|
|                  | µε     | µε     | µε     | µε     |
| I (3 ton)        | 216.3  | 243.8  | -158.8 | -173.4 |
| II (6 ton)       | 348.3  | 411.4  | -339.3 | -374.1 |
| III (9 ton)      | 495.6  | 544.7  | -420.9 | -532.8 |

* Bot: Bottom Chord
| Load Combination | Bot 01<sup>a</sup> | Bot 02<sup>a</sup> | Top 01<sup>b</sup> | Top 02<sup>b</sup> |
|------------------|------------------|------------------|------------------|------------------|
|                  | με               | με               | με               | με               |

<sup>b</sup> Top: Top Chord

Figure 8. FRP bridge prototype static load testing process (a) initial condition, (b) loading process, (c) collapse at Load III

Figure 9. Lateral deformation of top chord of the FRP bridges

5. Analysis and discussion

5.1. Numerical model
Fundamental frequencies referred to according to measurement results are 7.39 Hz and 8.06 Hz. Tuning model results obtained modulus of elasticity of 20830 MPa (for f=7.39 Hz) and 24930 MPa (for f=8.06 Hz) from the initial assumption of 20600 MPa.

Next, the comparison between deflection values generated by the simulation on the numerical model with the values measured in the test shown in Table 6.

| Table 6. Experimental and numerical analysis deflection values in every joint |
|----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                                | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
| Displacement (mm)              |     |     |     |     |     |     |     |     |     |
| Load I                         |     |     |     |     |     |     |     |     |     |
| Exp                          | -0.90 | -3.40 | -4.60 | -5.80 | -6.30 | -5.60 | -4.70 | -3.90 | -0.70 |
| Num b f=7.39                 | 0.00  | -2.45 | -4.58 | -6.15 | -6.82 | -6.15 | -4.58 | -2.45 | 0.00 |
| Num b f=8.06                 | 0.00  | -2.06 | -3.85 | -5.17 | -5.73 | -5.17 | -3.85 | -2.06 | 0.00 |
| Load II                       |     |     |     |     |     |     |     |     |     |
| Exp                          | -0.90 | -5.10 | -8.10 | -10.10 | -11.20 | -10.40 | -8.30 | -5.50 | -0.20 |
| Num b f=7.39                 | 0.00  | -4.91 | -9.16 | -12.30 | -13.65 | -12.30 | -9.16 | -4.91 | 0.00 |
| Num b f=8.06                 | 0.00  | -4.12 | -7.69 | -10.34 | -11.47 | -10.34 | -7.69 | -4.12 | 0.00 |
| Load III                      |     |     |     |     |     |     |     |     |     |
| Exp                          | -     | -     | -     | -     | -15.83 | -     | -     | -8.36 | 0.00 |
| Num b f=7.39                 | 0.00  | -7.36 | -13.73 | -18.46 | -20.47 | -18.46 | -13.73 | -7.36 | 0.00 |
| Num b f=8.06                 | 0.00  | -6.18 | -11.54 | -15.51 | -17.20 | -15.51 | -11.54 | -6.18 | 0.00 |

a Exp: Experimental  
b Num: Numerical analysis

Figure 10 illustrates the deformation of the FRP bridge prototype obtained from numerical and experimental simulations at each loading stage. Relative deflections of the bridge model obtained as L/1010 (for experimental models), L/781 (for numerical models f=7.39 Hz), dan L/930 (for numerical models f=8.06 Hz), where L is the total length of the bridge.

Those ratios were obtained in 9 tons loading, which still under L/200 in the AASHTO regulation. Even though the prototype collapsed at 9 tons, the deflection value still fulfilled the requirements. The results obtained indicate that the FRP bridge structure prototype has adequate structural stiffness.

Figure 10. Deflection of prototype FRP pedestrian bridge subjected to different static loading stages
5.2. Analysis of the causes of collapse

Although the bridge stiffness in the vertical direction is quite adequate, there are still other parts of the structure that have weaknesses. Figure 9 illustrates the deformation that occurs in the top chord due to the 6 tons loading with a maximum deformation value of 20 mm. Deformation, as in figure 8, allows the top chord to transfer compressive force and moments. When the load reaches 9 tons, the test model collapses at the top of the chord, as shown in Figure 11. This condition indicates that the top chord is a weak point in this prototype.

![Figure 9](image)

Figure 9. Deformation in the top chord due to 6 tons loading with a maximum deformation value of 20 mm

![Figure 10](image)

Figure 10. The condition of the bridge prototype after collapse

No. 1 in Figure 11 shows the first collapsed connection, then affects the nearest subsequent connection and members as shown in No. 2 connection. On the other side, No. 3 also has already shown damage, which is the occurrence of cracks which generally occur (Figure 12).

![Figure 11](image)

Figure 11. The condition of the bridge prototype after collapse

![Figure 12](image)

Figure 12. Crack location in no. 3 joint in figure 11

If strain results on one of the top chords analyzed, the stresses occur while the prototype collapses were:

\[
\sigma_{fail} = E \times e_{fail}
\]

\[
\sigma_{fail} = 20600 \times 532.8 \times 10^{-6}
\]

\[
\sigma_{fail} = 10.9 \text{ MPa}
\]

The compressive stress that occurs is still lower than the compressive strength, but the bridge has already failed. It is likely that the top chord not only holds the axial force but holds another force that occurs on its weak axis. An open truss system without this side support requires considerable stability in the compressive area.

The first prototype is only able to span less than 10 meters. When the first prototype was made to exceed that, with the bridge's own weight, the prototype had already suffered damage to the FRP profile and was less stable. After development, the second prototype is able to reach a span of 16 meters and has sufficient vertical stiffness and is stable enough to withstand its dead load and live load even though it still has shortcomings that must be evaluated.

6. Conclusion and recommendations

This article explains the identification of structural responses using a combined two open C channel pultruded-FRP-profile with a depth of 150 mm and a thickness of 7 mm due to dynamic and static load testing on a full-scale bridge planned used as an emergency pedestrian and light vehicle bridge. The prototype is a pony-truss bridge with 16 meters span and 2.5 meters wide. Dynamic test results showed
this prototype is rigid in the vertical direction but not rigid enough in the transverse direction of the bridge. The bridge prototype has been static tested until it collapses during the loading phase III (9 tons load), which planned to consist of four loading stages (maximum load of 12 tons). This FRP bridge prototype has adequate vertical stiffness because deflections obtained from static tests still meet permissible deflection requirements.

For further development of this research, the stiffness of the transverse direction of the bridge must increase. The recommendations is to increase the capacity of members which accept a compressive force by replacing FRP profiles that have a thicker web and flange profiles.

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References

[1] Sedlacek G 2004 Innovative developments for bridges ssing FRP composites Adv. Poly. Comp. Struc. Appli. Const.
[2] Bacinskas D 2017 Structural analysis of GFRP truss bridge model Mod. Build. Mat. Struct. Tech. MBMST 172 pp 68-74
[3] Kim S Y, Yoo J H Kim H Shin K Y and Yoon S J 2018 Failure modes of single and multi-bolted joint in the ultruded fiber polymer composite members
[4] Zhang X 2014 Life cycle ssessment (LCA) of fibre reinforced polymer (FRP) composites in civil application Eco Effic. Const. Build. Mat. pp 565-91
[5] Haak A J 2018 Life-cycle-cost Evaluation of Bridges with Fiber Reinforced Polymers (FRP) University of Rhode Island
[6] Potyrala P B 2011 Use of fibre reinforced polymer composites in bridge construction Sta. Art Hyb. All-Comp. Struc.(Barcelona: Universitat Politècnica de Catalunya)
[7] Bank L C 2006 Application of FRP composites tp bridges in USA Int. Coll. Appli. FRP Brid. (Japan Society of Civil Engineers) pp 9-16
[8] Correia J R, Gomes M M Pires J M and Branco F A 2013 Mechanical behaviour of pultruded glass fibre reinforced polymer composites at elevated temperature: experiments and model assessment Comp. Struc. 98 p 303–13
[9] Bazli M, Jafari A Ashrafi H Zhao X L Bai Y and Singh R K 2020 Effects of UV radiation, moisture and elevated temperature on mechanical properties of GFRP pultruded profiles Cons. Build. Mat. 231 p 117-37
[10] Riyono W A and Nasiri J 2019 Characterisation of C-shape pultruded fibre reinforced polymer for bridge structures Spri. Nat. Jour.
[11] Bakht B and Csagoly P F 1976 Lateral buckling of pony truss bridges Trans. Res. pp 14-8
[12] Butler M A, Swanson J A Rassati G A and Dues E F 2018 High resolution modeling and modeling of connections in pony truss bridges Trans. Res. Rec. Jour. Trans. Res. Boar. pp 1-10
[13] Singh S B and Chawla H 2018 An investigation of material characterization of pultruded FRP H- and I-beams Mech. Adv. Mat. Struc. 25 2
[14] Adi W 2013 Karacterisasi pultruded fiber reinforced polimer (PFRP) (Bandung: Pusat Penelitian dan Pengembangan Jalan dan Jembatan)