Self-supporting method; an alternative method for steel truss bridge element replacement

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Abstract. Steel truss bridge often requires replacement of its element due to serious damage caused by traffic accidents. This replacement is carried out using temporary supporting structure. It would be difficult when the available space for the temporary structure is quite limited and or the position of work is at a high elevation. The self-supporting method is proposed instead of temporary supporting structure. This paper will discuss an innovative method of bridge rehabilitation by utilizing the existing bridge structure. It requires such temporary connecting structure that installed on the existing bridge element, therefore, the forces during replacement process could be transferred to the bridge foundation directly. By taking the case on a steel truss bridge Jetis Salatiga which requires element replacement due to its damages on two main diagonals, a modeling is carried out to get a proper repair method. Structural analysis is conducted for three temporary connecting structure models: “I,” “V,” and triangular model. Stresses and translations that occur in the structure are used as constraints. Bridge bearings are modeled in two different modes: fixed-fixed system and fixed-free one. Temperature load is given in each condition to obtain the appropriate time for execution. The triangular model is chosen as the best one. In the fixed-fixed mode, this method can be carried out in a temperature range 27-28.8° C, while in fixed-free one, the temperature it is allowed between 27-43.4 °C. The D4 is dismantled first by cutting the D4 leaving an area of 1140.2 mm² or 127 mm web length to enable plastic condition until the D4 collapses. At the beginning of elongation occurs, immediately performed a slowly jacking on a temporary connecting structure so that the force on D4 is gradually transferred to the temporary connecting structure then the D4 and D5 are set in their place.

1. Introduction

Bridges are essential parts of the road system. The failure or impaired function of the bridges may limit the traffic, restrict the mobility in the network of people and goods, and leads to the economic loss for the community [1]. It is essential that particular attention is given to inspection of bridges as part of the management of road system.

According to Indonesian Bridge Management System (IBMS), the bridge maintenance includes routine maintenance, periodic maintenance, and rehabilitation. Rehabilitation includes repairing or replacement of upper structures, substructures and water flow arrangement. It is important to detect damage on bridge start from visual checking, defect detailing to computer modeling to ascertain the proper repair works and its method [2]. In the case of steel bridges, some treatments are the following:
crack repair, cleaning, cathodic protection, protective coating, strengthening, and member/element replacement [3].

Traffic accidents may cause damages on steel truss bridge structural element as the position of the main structure is commonly beside traffic lanes. In this case, truss elements often require replacement due to a serious defect. This replacement is carried out by using temporary supporting structure which is placed below the replaced element to support forces that occur at the time of replacement process. It would be difficult to execute when the available space for the temporary structure is quite limited and or the position of the replaced element is at a high elevation. Self-supporting method is proposed instead of temporary supporting structure. It does not require a temporary supporting structure while the forces that occur are accommodated by the existing structure until the replacement is successfully done.

The Jetis Bridge is an A40 steel truss bridge with 9 meters width. Caused by a traffic accident, two main diagonal truss elements (D4 and D5 on the right side) became ripped, twisted, and bent and needed to be replaced with the new ones [4]. Considering limited space around the bridge, the temporary supporting structure as the common method is not applicable. It needs another innovative method by utilizing the existing bridge structure as a self-supporting system. It requires such temporary connecting structure that installed on the existing bridge element, therefore, the forces during replacement process could be transferred to the bridge foundation directly. The method enables the new elements to connect well with minimum intervention to the structure.

2. Methodology

The study of the self-supporting method for steel truss bridge element replacement can be achieved by field measurement and structural analysis modeling. It requires dimension and field temperature data especially the temperature on work hours considering the time of replacement process. The detailed model may be developed taking into account actual dimension of the bridge.

Firstly, the structure was modeled as the actual condition before element replacements where the working load was dead load (upper structure self-weight: steel, concrete, and asphalt). The bearings were set as fixed-fixed at left abutment and fixed-free at right one. The outputs of this modeling were element stresses and node displacements. These data were then used as benchmarks on the next modeling.

Secondly, three (3) alternative shapes of connecting structure were designed and studied. The shapes are “l,” “V,” and triangular models. In structural analysis modeling, these models were attached to bridge structure to transfer forces to the foundation while the diagonal (D4) on the right side was dismantled. Each model would represent different behavior to steel structure, therefore, it can be determined which model would be chosen for replacement process.

Thirdly, the best connecting structure model was attached on bridge structure in modeling and analyzed to obtain the bridge element stresses and node displacements. Bridge bearings were modeled in two different conditions: fixed-fixed system and fixed-free one. The temperature load was applied from 27°C to certain value that results in xz-displacement as 2 mm.

2.1. Steel Truss Bridge

Truss bridge has been popular for hundreds of years. Steel became a common construction material for bridges, replacing timber and masonry construction to achieve longer span crossings. These structures are still functioning well, although the majority of them are now considered to have sub-standard capacity in the 21st century [5]. Truss elements have evolved from rods, bars, eyebars to box and H-shaped elements. Generally speaking, the box elements are more structurally efficient better than H-shapes, whereas H-shapes are perceived as being more economical regarding of fabrication and easier to connect to the gusset plates because of open access to bolts and easier to maintain because all surfaces are accessible [6].

Steel truss bridge usually contains top chords, bottom chords and diagonals, floor beams (cross girders), and stringers. Bearings support all load and transfer them to foundations. Lateral elements in
the plane of top and bottom chords resist wind loads and brace the compression chords and sway elements are thought to square the truss and increase its torsional rigidity.

Generally steel truss bridge in Indonesia uses steel with Fy=350 MPa (i.e Fe510C, ASTM A 572 grade 50, S355JO, HISTAR S460, or SM490) [7]. The connection among bridge elements is usually using bolts. This connection is considered to ease the transportation and erection process [8], usually uses MS (mild steel), HYS (high yield steel), ASTM A325 grade 8.8, or 10.9 HV bolts with tensile strength = 1000 MPa [7]. In modern steel bridge, prefabricated welded gusset plates connect all elements and eliminate the use of bolts [9].

Jetis Bridge is a Warren type truss without vertical which was built in 1998. With 39.972 m long and 9 m wide including pedestrian, it uses H-shaped elements for its top chords, bottom chords, diagonals, cross girders, stringers, wind bracings and sway elements. The actual dimensions of main elements are summarized in Table 1.

| No. | Element         | Dimension (mm)   | No.       | Element    | Dimension (mm)   |
|-----|-----------------|------------------|-----------|------------|------------------|
| 1   | Top chord       | H.340.400.10.13  | 5         | Diagonal 4-13 | H.336.249.9.12 |
| 2   | Bottom chord 1,3,4,5,6,8 | H.340.350.11.13  | 6         | Cross gird | H.947.225.12.21 |
| 3   | Bottom chord 2  | H.340.250.11.14  | 7         | Stringer   | H.447.152.8.10  |
| 4   | Diagonal 1,2,3,14,15,16 | H.340.350.12.13  |           |            |                  |

2.1.1. Load. Generally, Bridges are designed due to dead load, live load and environmental action i.e. temperature, the wind, flood, earthquake, and others [10]. Vehicle load is one of the most important factors to influence the structural safety and applicability of the highway bridge [11]. Design load in RSNI T-02-2005 is calculated according to statistical analysis of common occurrence. Especially in bridge rehabilitation, it needs temporary supports, load restrictions, or diverting traffic, typical courses of action exercised by road authorities during the remediation process [3]. In this case, only dead load, temperature load, and construction load are applied. The dead load consists of self weight of steel structure, concrete slab, concrete pedestrian, and asphalt layer. The temperature load is set to the ambient condition in the bridge location.

2.1.2. Boundary. Generally, The truss bridge boundaries in service condition are set to a fixed-free mode to provide longitudinal movement of the bridge, even in wide steel bridge, sometimes lateral movements of bridge are accommodated. The bridge behavior depends on moving mechanism of overall structure including its bearings [12]. Steel truss bridge usually uses elastomeric bearing which contains rubber at the top of bearing which is vulcanized to a steel plate [13]. In modeling of this element replacement process, these bearings are examined in two (2) different modes: fixed-fixed and fixed free to get the suitable method.

2.1.3. Temperature and displacement. Steel is quite sensitive to temperature change with its lengthening coefficient due to temperature is 12x10^-6 per°C [14]. The structural responses of bridge are deeply affected by the variation and distribution of temperatures on bridges [15]. Loads and temperature which work on structure results in displacements. Displacement/deflection characteristics are also used as an indicator to diagnose the presence of local damage [16]. In steel truss bridge, at abutment or pier, it is always provided such space to accommodate longitudinal movement. The Jetis Bridge is located in Salatiga, a city in Central Java Province which stretches along 7°17'00"–7°17'23" S and 110°27'56.81"–110°32'4.64" E [17]. Its average temperature is 23°C [18]. The onsite temperature data on May 20th-21st, 2017 were 27°C at 08.00 am, increased to 37°C at 11.00 am, and decreased to 27°C to at 05.00 pm. This data will be used in modeling to determine the temperature range for replacement execution.
2.2. Replacement method
False-work systems are frequently used in the construction, rehabilitation, and retrofit works of bridge structures [19], beside the cantilever method, float-ins, and tie-backs. Element replacement method can adopt the principles used in the bridge erection method. The method that commonly applied is false-work, by using temporary support structure below the bridge structure which is rested on the ground. This method is practical if the location is quite wide, the soil bearing capacity is adequate, and the bridge elevation is not high. With the self-supporting method, the use of this support is replaced by a temporary connecting structure that transmits loads to the foundation through the existing structure. With this method, the bridge element replacement at any location on the bridge can be done.

3. Result and Discussion
3.1. Modeling of initial condition
The initial condition was defined as the condition of the bridge at preparation stage of replacement without traffic live load. Dead load included upper structure self-weight, concrete deck slab, the asphalt layer and pedestrian concrete. The boundary condition was fixed-fixed at left abutment and fixed-free at right one. The structural model is shown in Figure 1 while the structural analysis result of this condition is summarized in Table 2 and Table 3.

![Figure 1. The initial model of bridge structure](image)

| No. | Element  | Stress (Mpa) | No. | Element  | Stress (Mpa) |
|-----|----------|--------------|-----|----------|--------------|
| 1   | Diagonal 1 | -91.62       | 17  | Top Chord 1 | -60.96       |
| 2   | Diagonal 2 | 96.24        | 18  | Top Chord 1 | -82.93       |
| 3   | Diagonal 3 | -81.13       | 19  | Top Chord 1 | -99.61       |
| 4   | Diagonal 4 | 96.76        | 20  | Top Chord 1 | -105.55      |
| 5   | Diagonal 5 | -69.42       | 21  | Top Chord 1 | -99.61       |
| 6   | Diagonal 6 | 67.09        | 22  | Top Chord 1 | -82.93       |
| 7   | Diagonal 7 | -39.19       | 23  | Top Chord 1 | -60.96       |
| 8   | Diagonal 8 | 34.71        | 24  | Bottom Chord 1 | 10.83 |
| 9   | Diagonal 9 | 34.71        | 25  | Bottom Chord 1 | 11.18 |
| 10  | Diagonal 10| -39.19       | 26  | Bottom Chord 1 | 12.31 |
| 11  | Diagonal 11| 67.09        | 27  | Bottom Chord 1 | 13.91 |
| 12  | Diagonal 12| -69.42       | 28  | Bottom Chord 1 | 13.91 |
| 13  | Diagonal 13| 96.76        | 29  | Bottom Chord 1 | 12.31 |
| 14  | Diagonal 14| -81.13       | 30  | Bottom Chord 1 | 11.18 |
| 15  | Diagonal 15| 96.24        | 31  | Bottom Chord 1 | 10.83 |
| 16  | Diagonal 16| -91.62       |     |            |              |

The translations especially located around D4-D5 are determined as benchmarks for the next modeling, which the xz-translation differences should not be more than 2 mm to fit the element bolts in their holes. The stresses on elements around replacement location should not be more than 325 MPa to avoid permanent deformation on the elements.
### Table 3. Node translations of bridge structure in initial mode

| No. | Element | xz-Translation (mm) | No. | Element | xz-Translation (mm) |
|-----|---------|---------------------|-----|---------|---------------------|
| 1   | D1      | 0.00                | 10  | TC1     | 8.29                |
| 2   | D2-D3   | 9.66                | 11  | TC1-TG2 | 14.61               |
| 3   | D4-D5   | 17.89               | 12  | TC2-TG3 | 21.12               |
| 4   | D6-D7   | 23.52               | 13  | TC3-TG4 | 24.60               |
| 5   | D8-D9   | 25.45               | 14  | TC4-TG5 | 24.56               |
| 6   | D10-D11 | 23.52               | 15  | TC5-TG6 | 20.97               |
| 7   | D12-D13 | 17.91               | 16  | TC6-TG7 | 14.28               |
| 8   | D14-D15 | 9.70                | 17  | TG7     | 7.59                |
| 9   | D16     | 0.88                |      |         |                     |

#### 3.2. Modeling of temporary connecting structure

The replacement process starts from dismantling the D4. Due to existing dead load, the forces on D4 is 558.69 kN. A temporary structure is required to transfer this forces to bridge structure when the D4 is dismantled. Three (3) models of the temporary connecting structure are examined starting from the simplest one. H.200.200.8.12 is taken to form the structure. The first is “I” shaped model which connects TC2 to the below node, therefore, the vertical force is handled. The second is “V” shaped model which replaces D4 and D5 roles temporarily. The third is a triangular model which is developed from “V” model with new horizontal beams to hold horizontal forces among the “V” ends.

![Initial model](initial.png)  ![“I” model](I.png)  ![“V” model](V.png)  ![Triangular model](triangular.png)

**Figure 2. Temporary connecting structure models**

From a structural analysis of the models, it can be described the strength and weakness of each one. The "V" and triangular models are applicable while the “I” model does not meet the requirements. Stresses and translations in each model are shown in Table 4 and Table 5 while the strength and weakness of each model are described in Table 6. To avoid slipping of the temporary connecting beam from the top chord while jacking process, the triangular model which has a horizontal lock is selected.
Table 4. Stresses of tested models

| No. | Element          | Stress (Mpa)       |
|-----|------------------|--------------------|
|     | initial condition| “I” model | “V” model | triangular model |
| 1   | Top Chord 2      | -82.93             | -232.09   | -94.05          | -59.24 |
| 2   | Diagonal 4       | 96.76              | -         | -             | -     |
| 3   | Diagonal 5       | -69.42             | -171.96   | -53.83          | -55.23 |
| 4   | Bottom Chord 2   | 11.18              | 90.78     | 11.60           | 12.56 |
| 5   | Bottom Chord 3   | 12.16              | 85.72     | 15.73           | 14.15 |

Table 5. Translations of tested models

| No. | Node       | xz-dir. deformation (mm) |
|-----|------------|--------------------------|
|     |            | initial condition | “I” model | “V” model | triangular model |
|     |            | Δ | δ | Δ | δ | Δ | δ | Δ |
| 1   | TC1-TC2    | 14.60 | 8.23 | 6.37 | 14.93 | -0.33 | 13.97 | 0.63 |
| 2   | TC2-TC3    | 21.18 | 36.79 | -15.61 | 21.31 | -0.13 | 20.39 | 0.79 |
| 3   | D4-D5      | 17.89 | 3.55 | 14.34 | 18.39 | -0.50 | 17.32 | 0.57 |

Table 6. Strength and weakness of tested model

| No. | Element          | Strength                      | Weakness                      | Remark         |
|-----|------------------|-------------------------------|-------------------------------|----------------|
| 1   | “I” model        | The simplest model, minimize material need | xz-translation >2 mm | unaccepted |
|     |                  |                               | Potentially endanger TC2     |                 |
| 2   | “V” model        | xz-translation difference < 2 mm and safe to structure | Horizontal forces on V tips are not held well, and more materials need | accepted |
| 3   | Triangular model | xz-translation difference < 2 mm and safe to structure | More materials need | accepted |

3.3. Modeling the combined influences of temperature and bearing system

The next step is modeling the combined influences of temperature and bearing system to the bridge structure. In the fixed-fixed mode, the longitudinal movement of the bearing is locked. It will resist the node displacements longitudinally, therefore, the node displacements are dominated only by vertical ones. In this mode the vertical displacement is expectedly quite small, therefore, the new elements can be placed easily. This mode will meet a problem when the replacement process is held on a day with high hourly temperature amplitude. The nodes will be higher than the initial condition elevations, and replacement process will be unapplicable.

The node displacement difference at replacement stage to the initial condition should not exceed 2 mm, because the bolt hole was made 2 mm larger than the bolt diameter in fabrication. If the displacement difference is exceeding 2 mm, the bolt can not be installed in its bolt-hole well. There are three important nodes that limit the modeling, the gusset TC2-TC1, TC2-TC3, and D4-D5 with a maximum displacement of 2 mm in one, two, or three of these gussets. The element stresses should not reach 325 MPa.

In the fixed-free mode, the longitudinal movement of the bearing is free on the right side. It will result in more displacements than in the fixed-fixed mode however the vertical displacements are fewer than in fixed-fixed mode in the same temperature amplitude. In this modeling, the combination of boundary modes and temperature load is applied from initial condition 27°C to higher temperature gradually. Stresses and translations of each combination are shown in Tables 7 and Table 8. In fixed-
fixed mode, this method can be carried out in a temperature range 27-28.8°C, while in fixed-free one, the temperature it is allowed between 27-43.4°C.

Table 7. Stresses Due To Boundary Mode and Temperature Load

| No | Element          | Stress (MPa) | fixed-free | fixed-fixed |
|----|------------------|--------------|------------|-------------|
|    |                  |              | T=27°C | T=43.4°C | T=27°C | T=28.8°C |
| 1  | Top Chord 2      | -82.93      | -232.09 | -94.05   | -59.24 |
| 2  | Diagonal 4       | 96.76       | -       | -        | -       |
| 3  | Diagonal 5       | -69.42      | -171.96 | -53.83   | -55.23 |
| 4  | Bottom Chord 2   | 11.18       | 90.78   | 11.60    | 12.56   |
| 5  | Bottom Chord 3   | 12.16       | 85.72   | 15.73    | 14.15   |

Table 8. Translations due to Boundary Mode and Temperature Load

| No. | Node       | Initial condition | boundary: Fixed-fixed | boundary: Fixed-free |
|-----|------------|-------------------|-----------------------|----------------------|
|     |            | δ                  | δ                     | Δ δ                   |
|     |            | T=27°C | T=43.4°C | T=27°C | T=28.8°C |
| 1   | TC1-TC2    | 14.60 | 13.97 | 0.63 | 13.92 | 1.58 | 13.49 | 1.11 | 12.94 | 1.66 |
| 2   | TC2-TC3    | 21.18 | 20.39 | 0.79 | 19.18 | 2.00 | 19.83 | 1.35 | 19.18 | 2.00 |
| 3   | D4-D5      | 17.89 | 17.32 | 0.57 | 16.97 | 0.92 | 16.91 | 0.98 | 16.49 | 1.40 |

Figure 3. Translations on fixed-fixed mode due to temperature load
3.4. Replacement method

Some considerations are needed to arrange the element replacement method including ambient temperature and its hourly amplitude, boundary support mode, temporary connecting structure dimension, displacements, stresses, and dismantling steps. These will influence the success of the replacement.

3.4.1. Element dismantling steps. To dismantle tension element (D4) from the structure, the temporary connecting structure should be installed first. This structure will receive the load transfer from D4 after it is released. To maintain safety when dismantling D4, it needs special treatment to transfer this force gradually. By knowing the tensile strength of steel material D4 and force that occurs on it, it can be conditioned so that the D4 has collapsed safely while the load is gradually transferred to the temporary connecting structure by slowly-jacking action. With 558.69 kN force and 490 MPa tensile strength steel, the D4 need to be ground/cut symmetrically and leaving 1140.2 mm² area or 126.69 mm length of its web to lead the plastic mechanism occurs.

3.4.2. Temporary connecting structure dimension. The temporary connecting structure uses doubled H.200.200.8.12 arranged in a triangular shape at both sides of D4 and D5 by leaving enough space for maneuver while the replacement is held. The total area of this H-arrangement is made slightly larger than the diagonal to provide sufficient safety when the temporary structure works.
3.4.3. Boundary mode selection. The combination of boundary mode and temperature load is very influential in the displacement that occurs. The mode selection in replacement depends on the temperature in the field when replacement takes place.

3.4.4. Jacking and tightening. Jacking is needed while attaching temporary connecting structure to existing bridge and load transfer process from D4. To ensure the force transferred entirely to the temporary connecting structure, the jacking will be followed by tightening using threaded fasteners. The jacking uses a hydraulic jack of 150 tons considering the forces that occur on the elements.

Considering some requirements above, it can be defined the element replacement method of steel truss bridge as shown in Figure 6.

Figure 6. Detail position of temporary connecting structure

Figure 7. Flowchart of bridge element replacement method
4. Conclusion

Bridge rehabilitation is important in road system to maintain the transportation function to run well. One of rehabilitation work in steel truss bridge is the replacement of its element due to damages. In a condition where the commonly used method is unappplicable caused by limited space of work, high elevation and low bearing capacity of the soil, the self-supporting method is appropriate for steel truss bridge in its element replacement. By taking the case on a steel truss bridge Jetis Salatiga which requires element replacement due to its defects on two (2) diagonals, it can be concluded that the bridge element replacement depends on some factors such as space availability, elevation, soil strength, temperature, and tools.

The method taken should be appropriate to the existing bridge and avoid any damages to the bridge. Element stresses are very significant to be concerned. Overstressed element may cause a new problem for bridge structure. Bolt precision becomes a certain parameter for the success of replacement method and ambient temperature which leads the structure behavior should be considered well.

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