Maximum deflection of simple span steel box girder bridge using stress data

M. Suangga¹,², David Surachmat²

¹Civil Engineering Department, Faculty of Engineering, Bina Nusantara University Jakarta, Indonesia 11480
²Master Program in Civil Engineering, Tarumanagara University, Jakarta, Indonesia 11480

Corresponding author: suangga@binus.edu

Abstract. The Structural Health Monitoring System is part of tool and method for bridge operation and maintenance to make sure that the bridge is in good condition. Deflection is one of the main parameters to be measured and various methods has been introduced to measure deflection. Accuracy and economically are two main aspects when selecting the method for determine the real time deflection. This study presents a method of determining the maximum deflection of simple span continuous bridge using strain data obtained from a strain gauge sensor for simple span steel box girder bridge. Initial data were obtained from FEM simulations under various load conditions to obtain the maximum deflection value and the strain value. Linear regression and quadratic regression were carried out to obtain the relationship between the strains data and the maximum deflection. The accuracy of the maximum deflection value is then compared with the results of the analysis using FEM. It was found that the accuracy is about 91.16 % for quadratic regression and 9.07 for linear regression 90.93 %.

Keywords: Bridges, Structural Health Monitoring Systems, Maximum Deflection, Strain

1. Introduction

The bridge is a connecting construction crossing the obstacle such as rivers, roads, and other physical obstacles. To ensure that the bridge is always in good condition, an effort is needed to monitor the condition of the bridge structure called a structural health monitoring system. Structural health monitoring aims to detect structural damage, predict the service life of the structure, and provide data so that the maintenance process is as optimal as possible in terms of cost (Liu, 2009). In the last few decades, computer-based structural health monitoring systems have been implemented so that structural health information is obtained in a timely, sustainable, and economical manner (Brownjohn, 2006).

Vertical deflection is a very important parameter to be monitored to ensure the bridge remains in adequate condition. There are many ways that can be done to monitor the condition of the bridge, one of which is by using GPS. According to Haripriambodo (2019), although it produces accurate data, the use of GPS is seen as a relatively large cost. A more practical and inexpensive solution to predict deflection is to use a strain gauge then predicting the maximum deflection using equation from strain
data. Therefore, it is important to know the deflection correlation of the strain data and its accuracy. A better understanding of the relationship between deflection and strain, will make it easier for practitioners to assess the condition of the bridge based on deflection economically.

2. Objectives

The objective of the research is to obtain a maximum deflection equation based on strain data on a simple span steel box girder bridge modeled with a 3-dimensional finite element model and to determine the accuracy of the maximum deflection - strain equation.

3. Methodology

The methodology of this research is as follow
a. The research was carried out using the simple span steel box girder bridge data located at Java, Indonesia. The bridge is under design stage
b. Two-dimensional Finite Element Method model of the bridge is developed for this study
c. The actual maximum deflection and stress and strain data are obtained by applying various load condition to the 2-dimensional Finite Element Method model of the bridge.
d. Equations to calculate maximum deflection from strain data is obtained by implementing Multiple Regression which using Statistics software.
e. The maximum deflection obtained using the statistic equation then verified by comparing the value with the maximum deflection obtained from 2D structural analysis using the FEM structure analysis software.

4. Case Study

The case study used for this study is simple span steel box girder with a span of 60 m. The longitudinal and transversal sections of the bridge are presented in Figures 1 and Figure 2.

Figure 1. Longitudinal Section of the Bridge

Figure 2. Cross Section of The Bridge
Two-dimensional Finite Element Model of the bridge has been developed to represent the actual condition of the bridge. The stress and strain is measured at the middle of the bridge span as illustrated in Figure 3.

![Figure 3. Two-dimensional finite element modelling of the bridge](image)

5. Maximum Deflection and Stress/Strain Data

To generate the maximum deflection and stress data, 87 load configurations are considered. Sample of Load Configurations are presented in Table 1. The maximum deflection value based Two-dimensional FEM analysis are sorted by the smallest deflection and presented in Table 2.
Table 2 Two-dimensional FEM results sorted by the smallest deflection

| Load Config. | δ (mm) | σt (N/mm²) | Load Config. | δ (mm) | σt (N/mm²) | Load Config. | δ (mm) | σt (N/mm²) |
|--------------|--------|-------------|--------------|--------|-------------|--------------|--------|-------------|
| PB58         | -2.194 | 3.337       | PB62         | -12.8037 | 23.052      | PB24         | -22.7578 | 47.863      |
| PB1          | -3.0735| 4.884       | PB86         | -12.8061 | 22.271      | PB84         | -23.0422 | 41.807      |
| PB15         | -3.0735| 4.884       | PB5          | -13.4894 | 24.42       | PB23         | -23.3793 | 54.7        |
| PB72         | -3.2976| 6.447       | PB11         | -13.4894 | 24.42       | PB77         | -25.6075 | 46.104      |
| PB16         | -4.303 | 6.838       | PB68         | -13.8035 | 25.787      | PB35         | -26.9788 | 48.839      |
| PB30         | -4.303 | 6.838       | PB63         | -14.5828 | 27.932      | PB41         | -26.9788 | 48.839      |
| PB73         | -4.3881| 6.675       | PB6          | -15.1542 | 29.304      | PB83         | -27.6069 | 51.574      |
| PB59         | -5.1827| 8.4         | PB10         | -15.1542 | 29.304      | PB78         | -29.1655 | 55.872      |
| PB71         | -6.0431| 11.135      | PB67         | -15.3605 | 30.671      | PB36         | -30.3084 | 58.607      |
| PB2          | -6.0532| 9.768       | PB64         | -15.8181 | 32.429      | PB40         | -30.3084 | 58.607      |
| PB14         | -6.0532| 9.768       | PB19         | -15.897  | 27.35       | PB82         | -30.7211 | 61.342      |
| PB31         | -6.1471| 9.768       | PB27         | -15.897  | 27.35       | PB81         | -31.5211 | 71.094      |
| PB45         | -6.1471| 9.768       | PB75         | -16.0195 | 26.569      | PB79         | -31.6361 | 64.859      |
| PB87         | -6.5951| 12.894      | PB7          | -16.2556 | 34.188      | PB37         | -32.511  | 68.375      |
| PB60         | -8.0098| 13.367      | PB9          | -16.2556 | 34.188      | PB39         | -32.511  | 68.375      |
| PB17         | -8.4744| 13.675      | PB66         | -16.2605 | 35.555      | PB80         | -32.8307 | 72.087      |
| PB29         | -8.4744| 13.675      | PB65         | -16.4154 | 36.043      | PB38         | -33.399  | 78.143      |
| PB70         | -8.805 | 16.54       | PB88         | -16.6995 | 39.072      | PB80         | -62.1    | 117.215     |
| PB3          | -8.845 | 14.652      | PB85         | -17.6099 | 33.081      | PB51         | -62.1    | 117.215     |
| PB13         | -8.845 | 14.652      | PB33         | -17.6899 | 29.304      | PB46         | -124.2   | 234.429     |
| PB74         | -10.3653| 16.801      | PB43         | -17.6899 | 29.304      | PB52         | -124.2   | 234.429     |
| PB61         | -10.5814| 18.168      | PB20         | -18.8852 | 34.188      | PB13         | -124.2   | 234.429     |
| PB4          | -11.355| 19.536      | PB26         | -18.8852 | 34.188      | PB47         | -248.5   | 468.858     |
| PB12         | -11.355| 19.536      | PB76         | -21.1629 | 36.337      | PB54         | -310.6   | 586.073     |
| PB69         | -11.9211| 20.903      | PB21         | -21.2159 | 41.025      | PB55         | -310.6   | 586.073     |
| PB32         | -12.1063| 19.536      | PB25         | -21.2159 | 41.025      | PB48         | -621.2   | 1172.146    |
| PB44         | -12.1063| 19.536      | PB34         | -22.71   | 39.072      | PB56         | -621.2   | 1172.146    |
| PB18         | -12.3829| 20.513      | PB42         | -22.71   | 39.072      | PB87         | -621.2   | 1172.146    |
| PB28         | -12.3829| 20.513      | PB22         | -22.7578 | 47.863      | PB49         | -1242.4  | 2344.292    |

6. Regression Equation to Determine Maximum Deflection

The deflection and stress values presented in Table 2 then processed by multiple regression analysis to obtain a maximum deflection – stress regression equation. The regression equations are presented in Equation 1 and Equation 2 for Linear regression and Quadratic Equation.

a. Linear regression

\[ \delta = 0.139 - 0.530 \sigma_t \]  

(1)

b. Quadratic Regression

\[ \delta = 0.081 - 0.529 \sigma_t - 6.126 \times 10^{-7} \sigma_t^2 \]

(2)
7. Accuracy of the Maximum Deflection Value

The accuracy of the approach has been investigated by comparing the maximum deflection from FEM model with the maximum deflection from the regression equation. The result of accuracy check is presented in Table 3.

**Table 3.** Maximum Deflection from FEM Analysis vs Deflection from Regression Equation sorted by smallest deflection

| Load Config. | \( \delta \) FEM (mm) | Linear Regression | Quadratic Regression |
|--------------|----------------|------------------|------------------|
|              | \( \delta \) Equation (mm) | \( \Delta \) (mm) (%) | \( \delta \) Equation (mm) | \( \Delta \) (mm) (%) |
| PB58         | -2.194           | -1.62883 0.56517186 25.759884 | -1.68407 0.50993515 23.2420915 |
| PB1          | -3.0735          | -2.44856 0.62493775 20.333097 | -2.50212 0.57138118 18.5905688 |
| PB15         | -3.0735          | -2.44856 0.62493775 20.333097 | -2.50212 0.57138118 18.5905688 |
| PB72         | -3.2976          | -3.27677 0.02082546 0.63153383 | -3.32863 0.031039 0.94107735 |
| PB16         | -4.403           | -3.48396 0.81903992 19.034164 | -3.53539 0.76760583 17.8388529 |
| PB30         | -4.403           | -3.48396 0.81903992 19.034164 | -3.53539 0.76760583 17.8388529 |
| PB73         | -4.3881          | -3.39759 0.99051138 22.572671 | -3.4492 0.93890044 21.3965139 |
| PB59         | -5.1827          | -4.31164 0.87105751 16.807022 | -4.36138 0.82131688 15.8472763 |
| PB71         | -6.0431          | -5.76088 0.28221847 4.67009444 | -5.80766 0.23543566 3.89594053 |
| PB2          | -6.0532          | -5.03653 1.01667305 16.795630 | -5.08479 0.96841294 15.9983634 |
| PB14         | -6.0532          | -5.03653 1.01667305 16.795630 | -5.08479 0.96841294 15.9983634 |
| PB31         | -6.1471          | -5.03653 1.11057305 18.066618 | -5.08479 1.06231290 17.2815301 |
| PB45         | -6.1471          | -5.03653 1.11057305 18.066618 | -5.08479 1.06231290 17.2815301 |
| PB87         | -6.5951          | -6.69295 0.09785153 1.48370005 | -6.73784 0.142737 2.16288088 |
| PB60         | -8.0098          | -6.94359 1.06621225 13.311347 | -6.98796 1.02183642 12.7573273 |
| PB17         | -8.4744          | -7.10679 1.36760727 16.138101 | -7.15084 1.32356310 15.6183694 |
| PB29         | -8.4744          | -7.10679 1.36760727 16.138101 | -7.15084 1.32356310 15.6183694 |
| PB70         | -8.805           | -8.62492 0.18008301 2.04523588 | -8.66588 0.13911854 1.57999434 |
| PB3          | -8.845           | -7.62449 1.22050835 13.798851 | -7.66748 1.17751555 13.3127814 |
| PB13         | -8.845           | -7.62449 1.22050835 13.798851 | -7.66748 1.17751555 13.3127814 |
| PB74         | -10.3653         | -8.76322 1.60208268 15.456211 | -8.8039 1.56139822 15.0637052 |
| PB61         | -10.581          | -9.48757 1.09382811 10.337272 | -9.52679 1.05460911 9.96663106 |
| PB4          | -11.355          | -10.2125 1.14254365 10.062031 | -10.2502 1.10478889 9.72936461 |
| PB12         | -11.355          | -10.2125 1.14254365 10.062031 | -10.2502 1.10478889 9.72936461 |
| PB69         | -11.5211         | -10.9368 0.58428907 5.07146959 | -10.9731 0.54799551 4.75648412 |
| PB32         | -12.1063         | -10.2125 1.89384365 15.643455 | -10.2502 1.85608889 15.3315948 |
| PB44         | -12.1063         | -10.2125 1.89384365 15.643455 | -10.2502 1.85608889 15.3315948 |
| PB18         | -12.3829         | -10.7302 1.65274473 13.346992 | -10.7669 1.61603430 13.0505314 |
| PB28         | -12.3829         | -10.7302 1.65274473 13.346992 | -10.7669 1.61603430 13.0505314 |
### Table 3. Maximum Deflection from FEM Analysis vs Deflection from Regression Equation sorted by smallest deflection (continued)

| Load Config. | δ FEM (mm) | Linear Regression | Quadratic Regression |
|--------------|------------|-------------------|----------------------|
|              | δ Equation (mm) | Δ (mm) (%) | δ Equation (mm) | Δ (mm) (%) |
| PB62         | -12,8037   | -12,0755 0,728163 | 5,687133 | -12,1095 0,694161 | 5,421569 |
| PB86         | -12,8061   | -11,6617 1,144405 | 8,936402 | -11,6965 1,10957 | 8,664389 |
| PB5          | -13,4894   | -12,8004 0,688979 | 5,107558 | -12,833 0,656433 | 4,866287 |
| PB11         | -13,4894   | -12,8004 0,688979 | 5,107558 | -12,833 0,656433 | 4,866287 |
| PB68         | -13,8035   | -13,5248 0,278724 | 2,01923 | -13,5559 0,247631 | 1,793973 |
| PB63         | -14,5828   | -14,6614 0,078582 | 0,538866 | -14,6902 0,1074 | 0,736485 |
| PB6          | -15,1542   | -15,3884 0,234186 | 1,545352 | -15,4158 0,261552 | 1,725938 |
| PB10         | -15,1542   | -15,3884 0,234186 | 1,545352 | -15,4158 0,261552 | 1,725938 |
| PB67         | -15,3605   | -16,1127 0,75224 | 4,897239 | -16,1387 0,778162 | 5,065995 |
| PB64         | -15,8181   | -17,0443 1,22618 | 7,751756 | -17,0683 1,250248 | 7,903908 |
| PB19         | -15,897    | -14,353 1,540012 | 9,7126 | -14,3824 1,514577 | 9,527439 |
| PB27         | -15,897    | -14,353 1,540012 | 9,7126 | -14,3824 1,514577 | 9,527439 |
| PB75         | -16,0195   | -13,9391 2,080353 | 12,98638 | -13,9694 2,05009 | 12,79747 |
| PB7          | -16,2556   | -17,9764 1,72075 | 10,58559 | -17,9986 1,742966 | 10,72225 |
| PB9          | -16,2556   | -17,9764 1,72075 | 10,58559 | -17,9986 1,742966 | 10,72225 |
| PB66         | -16,2605   | -18,7007 2,440205 | 15,00695 | -18,7215 2,460985 | 15,13474 |
| PB65         | -16,4154   | -18,9593 2,54389 | 15,49697 | -18,9796 2,564157 | 15,62044 |
| PB8          | -16,6995   | -20,5643 3,868415 | 23,1433 | -20,5814 3,88191 | 23,24567 |
| PB85         | -17,6099   | -17,3898 0,220134 | 1,250056 | -17,4131 0,196753 | 1,117286 |
| PB33         | -17,6899   | -15,3884 2,301514 | 13,01033 | -15,4158 2,274148 | 12,85563 |
| PB43         | -17,6899   | -15,3884 2,301514 | 13,01033 | -15,4158 2,274148 | 12,85563 |
| PB20         | -18,8852   | -17,9764 0,90885 | 4,812496 | -17,9986 0,886634 | 4,694859 |
| PB26         | -18,8852   | -17,9764 0,90885 | 4,812496 | -17,9986 0,886634 | 4,694859 |
| PB76         | -21,1629   | -19,1151 2,047824 | 9,67648 | -19,135 2,027865 | 9,582169 |
| PB21         | -21,2159   | -21,5992 0,383283 | 1,806584 | -21,6142 0,398338 | 1,877546 |
| PB25         | -21,2159   | -21,5992 0,383283 | 1,806584 | -21,6142 0,398338 | 1,877546 |
| PB34         | -22,71     | -20,5643 2,145685 | 9,448194 | -20,5814 2,12859 | 9,372919 |
| PB42         | -22,71     | -20,5643 2,145685 | 9,448194 | -20,5814 2,12859 | 9,372919 |
| PB22         | -22,7578   | -25,2225 2,464746 | 10,83033 | -25,2305 2,472696 | 10,86527 |
Table 3. Maximum Deflection from FEM Analysis vs Deflection from Regression Equation sorted by smallest deflection (continued)

| Load Config. | δ FEM (mm) | Linear Regression | Quadratic Regression |
|--------------|------------|-------------------|----------------------|
|              | δ Equation (mm) | Δ (mm) | (%) | δ Equation (mm) | Δ (mm) | (%) |
| PB24         | -22.7578   | -25.2225          | 2.46476              | 10.83033   | -25.2305          | 2.472696 | 10.86527 |
| PB84         | -23.0422   | -22.0136          | 1.028646             | 4.464182   | -22.0278          | 1.014406 | 4.402383 |
| PB23         | -23.3793   | -28.8454          | 5.466078             | 23.37999   | -28.8463          | 5.466983 | 23.38863 |
| PB77         | -25.6075   | -24.2905          | 1.317024             | 5.14312    | -24.3002          | 1.307252 | 5.104956 |
| PB35         | -26.9788   | -25.7397          | 1.239085             | 4.592811   | -25.7467          | 1.232144 | 4.567082 |
| PB41         | -26.9788   | -25.7397          | 1.239085             | 4.592811   | -25.7467          | 1.232144 | 4.567082 |
| PB83         | -27.6069   | -27.189           | 0.417946             | 1.51392    | -27.1931          | 0.413827 | 1.498999 |
| PB78         | -29.1655   | -29.4664          | 0.300905             | 1.031716   | -29.4661          | 0.300607 | 1.030695 |
| PB36         | -30.3084   | -30.9156          | 0.607244             | 2.00355    | -30.9125          | 0.604148 | 1.993334 |
| PB40         | -30.3084   | -30.9156          | 0.607244             | 2.00355    | -30.9125          | 0.604148 | 1.993334 |
| PB82         | -30.7211   | -32.3649          | 1.643783             | 5.350665   | -32.359           | 1.637897 | 5.331506 |
| PB81         | -31.5211   | -37.5323          | 6.011234             | 19.07051   | -37.5166          | 6.005476 | 19.02052 |
| PB79         | -31.6361   | -34.2285          | 2.592393             | 8.194415   | -34.219           | 2.582934 | 8.164513 |
| PB37         | -32.511    | -36.0916          | 3.580573             | 11.01342   | -36.0786          | 3.567556 | 10.97338 |
| PB39         | -32.511    | -36.0916          | 3.580573             | 11.01342   | -36.0786          | 3.567556 | 10.97338 |
| PB80         | -32.8307   | -38.0585          | 5.227811             | 15.92355   | -38.0418          | 5.211055 | 15.87251 |
| PB38         | -33.399    | -41.2675          | 7.868503             | 23.5591    | -41.2447          | 7.845682 | 23.49077 |
| PB50         | -62.1      | -61.9712          | 0.12878              | 0.207374   | -61.9104          | 0.189647 | 0.30539  |
| PB51         | -62.1      | -61.9712          | 0.12878              | 0.207374   | -61.9104          | 0.189647 | 0.30539  |
| PB46         | -124.2     | -124.081          | 0.118686             | 0.095561   | -123.918          | 0.282468 | 0.22743  |
| PB52         | -124.2     | -124.081          | 0.118686             | 0.095561   | -123.918          | 0.282468 | 0.22743  |
| PB53         | -124.2     | -124.081          | 0.118686             | 0.095561   | -123.918          | 0.282468 | 0.22743  |
| PB47         | -248.5     | -248.302          | 0.19797              | 0.079666   | -247.983          | 0.517077 | 0.208079 |
| PB54         | -310.6     | -310.413          | 0.187348             | 0.060318   | -310.041          | 0.558865 | 0.179931 |
| PB55         | -310.6     | -310.413          | 0.187348             | 0.060318   | -310.041          | 0.558865 | 0.179931 |
| PB48         | -621.2     | -620.965          | 0.235293             | 0.037877   | -620.584          | 0.616341 | 0.099218 |
| PB56         | -621.2     | -620.965          | 0.235293             | 0.037877   | -620.584          | 0.616341 | 0.099218 |
| PB57         | -621.2     | -620.965          | 0.235293             | 0.037877   | -620.584          | 0.616341 | 0.099218 |
| PB49         | -1242.4    | -1242.07          | 0.331183             | 0.026657   | -1242.93          | 0.531311 | 0.042765 |
| **Average**  |           | **1.335541**      | **9.0757**           | **1.353634** | **8.848111**      |
It can be seen in Table 3 that the average difference of FEM maximum deflection and regression equation is 8.84% for quadratic regression and 9.07 for linear regression. The difference in maximum deflection value is relatively small. The difference for PB 19, PB 22, PB 24 and PB 26 are relatively high, these are due to the relatively small deflection value of the load configuration considered.

8. Conclusion and Recommendation

Based on the results of the analysis of the research conducted, it can be concluded that:

a. This study shows that the application of regression formula to predict the maximum deflection value at simple span steel box girder bridge provide relatively good accuracy.

b. Therefore, strain gauge sensor can be utilized to measure the strain for maximum deflection of bridge to provide economical structural monitoring system.

c. The accuracy increases by using higher order of regression.

d. It is suggested to conduct field test application of the system in the real bridge.

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