Disease Analysis for “Single Plate Bearing” in Plate Girder Bridge and Its Strengthening Scheme

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Abstract. The phenomenon of “single plate bearing” is one of the diseases in plate girder bridges. In order to study its mechanical characteristics and strengthening schemes, with the help of finite element software ANSYS, “single plate bearing” of plate girder bridge is simulated numerically in this section. Firstly, models are simulated with beam element, and transversal distribution rule of load is analysed. Then according to the mechanical behavior of plate girder bridge and the reason leading to “single plate bearing”, five strengthening schemes are proposed to delay or avoid “single plate bearing” and their spatial models are built with solid element Mechanical behaviors such as displacement, stress are contrasted and analysed. Furthermore, transversal stress at hinged joints is analysed in detail, and it is proposed that the adhesive strength between new and old concrete should be applied to test transversal stress at hinged joints. At last according to the merit and demerit of five strengthening schemes, feasible schemes for “single plate bearing” are given.

1. Introduction
With our economy fast developing and transport market drastic contest, overload has increased rapidly; as a result, road facilities have been damaged seriously. Especially plate highway bridges have been damaged heavily and even destroyed. The damage of plate girder bridge mainly is shown in the concrete at hinged joints cracking completely. It leads to transversal connection damaged and single plate bears wheel loads, generally it is called “single plate bearing” [1-4]. It has heavily destroyed bridge entirety, and decreased bridge carrying capacity, and brought about incipient fault to safe driving. There are many reasons for single plate bearing including design, construction, operation and structural characteristics and so on. With the help of finite element software ANSYS, it has been analyzed specifically and some corresponding technical measures have been proposed.

2. Disease Analysis for Single Plate Bearing

2.1. Model Built with Beam Element
Generally, small bridges are hinged plate girder bridge, and each plate is connected with hinged joints which only transfer shear and cannot bear moment. During numerical imitation hinged joints are imitated with beam element and their nodes are released through setting their attribute, that is to say,
they are simulated with stiff links, and all the rotations of one end are released to ensure finite element model consistent with actual conditions of bridge. During model being built cellular plate bridges are set as an example which are composed of 11 plates, and their spans are 8m, 13m and 16m respectively. Figure 1 shows an 8m-span bridge model, and in the figure hinged joints are simulated with beam element and concrete plate with plane element [5-7].

**Figure 1.** Model of whole bridge built with beam element.

**Figure 2.** Distribution coefficient of 8m-span bridge.

### 2.2. Transversal Distribution Rule of Loads

Figure 2 shows transversal distribution coefficient for 8m-span plate girder bridge, and N1 and N2 etc. present the code of plate. Transversal distribution curve for 13 m and 16m-span is similar to that of 8m-span bridge, however there are obvious differences in number shown in table 1. When load is applied at side plate, transversal distribution curve is the most un-uniform; when load place tends gradually to the middle place, the curve becomes smooth and its amplitude of distribution coefficient decrease, namely load distribution tends to uniformity.

From table 1 we can see, under the same load and at the same applied place, distribution coefficient of different span bridge is different. When load is applied at middle plate, distribution coefficient of 8m-span bridge changes within 0.295 and 0.034; And that of 16m-span bridge changes within 0.192 and 0.061. When load is applied at side plate, distribution coefficient of 8m-span bridge changes within 0.426 and 0.007; and that of 16m-span bridge changes within 0.275 and 0.034, especially distribution coefficient at the other side of 8m-span bridge is 0.007 and its load is almost zero. Analysed from the mechanics viewpoint, at the same load condition, transversal constrain becomes relatively weaker with span increasing, and the bridge becomes more like a slender beam, so it is in favour of transversal distribution of load.

**Table 1.** Transversal distribution coefficient contrast of different span plate girder bridge.

| Load place | 8m  | 13m | 16m | 8m  | 13m | 16m |
|------------|-----|-----|-----|-----|-----|-----|
| Middle plate | 0.295 | 0.217 | 0.192 | 0.034 | 0.055 | 0.061 |
| Side plate  | 0.426 | 0.314 | 0.275 | 0.007 | 0.024 | 0.034 |

In conclusion, load transversal distribution coefficient is connection with not only load place but also span. With span decreasing, its un-uniformity is becoming more obvious. Therefore, 8m-span bridge is set as an example in the following analysis. During actual investigation, we have found that single plate bearing only appears in small bridge, gangway culvert and other small structures, and it seldom occurs in long and middle span bridges. Moreover, this phenomenon is relatively more severe in 8m-span bridges. It is consistent with theoretical analysis.
2.3. Moment Distribution of 8m-span Plate Girder Bridge

Through numerical simulation, the moment graph of each plate is drawn under unit load applied at span centre. When unit load is applied at N1, N4 and N6, moment graphs are shown in figures 3-5. We can see clearly spatial distribution curve of moment at different load place. Along longitudinal direction, the moment graph of each plate appears in delta-shape, and the moment at midspan is the maximum. Along transversal direction, the moment graph is curve, and it is consistent with the curve of transversal distribution coefficient. On the other hand, the sum of all plate moment is 2 N·m, and it is the same as moment when unit load is applied at midspan of simply supported beam. It proves the correctness of models built with beam element.

![Figure 3](image1.png) **Figure 3.** Moment of each plate under unit load applying at plate N1.

![Figure 4](image2.png) **Figure 4.** Moment of each plate under unit load applying at plate N4.

![Figure 5](image3.png) **Figure 5.** Moment of each plate under unit load applying at plate N6.

3. Strengthening Schemes for Single Plate Bearing

According to the mechanical behavior of plate girder bridge and the reason leading to “single plate bearing”, five strengthening schemes are proposed to delay or avoid “single plate bearing” [8, 9]. During contrast and selection, the spatial models with solid element are built in order to reflect actual problems accurately. Mechanical behaviors such as displacement, stress and so on are contrasted and analyzed [10, 11].

3.1. Description of Solid Element Models

In principle solid model of whole bridge should be built, but considering that computing scale is too large, the model is simplified properly during model building. Only considering that truck super-20 is applied in midspan area, according to transverse distribution rule of load, distribution loads of each plate are calculated respectively [7, 8]. Then these loads are applied to solid models and calculation and analysis are done more accurately. When load is applied at midspan (N5 and N7), the model is shown in figure 6, and distribution loads of each plate are shown in table 2. From it we can see that the sum of loads of N5, N7 and middle plate (N6) accounts to 56.7 percent. That is to say concentrated load is mainly distributed at three plates. Therefore, in order to illustrate problems simply, solid element model of five plates (N4, N5, N6, N7 and N8) is built only.

![Figure 6](image4.png) **Figure 6.** Load diagrammatic view of finite element model.
Table 2. Distribution load of each plate.

| Load place | Load of each plate /N |
|------------|-----------------------|
| N1         | 3680                  |
| N2         | 4412                  |
| N3         | 6145                  |
| N4         | 9887                  |
| N5         | 20717                 |
| N6         | 9697                  |
| N7         | 5733                  |
| N8         | 3703                  |
| N9         | 2541                  |
| N10        | 1890                  |
| N11        | 1596                  |
| Sum force  | 5276                  |
|            | 6302                  |
|            | 8686                  |
|            | 13590                 |
|            | 26450                 |
|            | 26450                 |
|            | 13590                 |
|            | 8685                  |
|            | 6302                  |
|            | 5276                  |

Now 8m-span bridge is set as an example and three dimension model of local region is built with finite element software ANSYS. It contains models of existing bridge and five strengthening schemes as following:

Scheme 1 is adding reinforcements in hinged joints;
Scheme 2 is adding steel plates (0.06 m×0.21 m×0.008 m) at bottom plate of hinged joints;
Scheme 3 is adding steel plates (0.06 m×0.21 m×0.008 m) at upper plate of hinged joints, at intervals of 1 m;
Scheme 4 is increasing the beam height 10 percent;
Scheme 5 is adding transversal prestress (1000 MPa) at bottom plate of bridge, at intervals of 1 m.

In FEM analysis, concrete and hinged joints are simulated with solid element of 8 nodes, reinforcements are simulated with beam element of 2 nodes, prestrees is simulated with equivalent load. Element size is controlled in 0.2m. In order to calculate simply, only dead load are considered.

3.2. Analysis of Finite Element Results

Analysis detail of structure mainly contains static, modal and time history analysis. During analysis it is found that the dynamic results of each scheme is basically the same, therefore only static analysis is introduced here. In static analysis tension stress is positive and compression stress is negative. Total displacement \( f \) is the vector sum of vertical, transversal and longitudinal displacements. In order to illustrate problems thoroughly, equivalent stress \( \sigma_e \) is introduced:

\[
\sigma_e = \left\{ \frac{1}{3} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \right\}^{\frac{1}{2}} \quad (1)
\]

where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are principal stresses. Distribution rule of displacement and stress at upper and bottom plates is basically consistent, moreover bottom plate is in compressive state under loads, so only distribution rule of displacement and stress at bottom plates is analysed.

3.2.1. Transversal Distribution Rule of Displacement and Stress at Bottom Plates. From transversal distribution graph shown in figure 7 we can see that transversal distribution tendency of existing bridge and each strengthening scheme is basically same, and displacement changes little along transversal direction. Displacement of scheme 1 and existing bridge is almost same in number, but there exist obvious differences between existing bridge and the other schemes. After strengthening the maximum displacement decreases 15%, 10%, 13% and 16% respectively. Strengthening effectiveness is different: firstly adding plate at bottom and transversal prestress, and secondly increasing beam height.

From equivalent stress (see figure 8) we can see that stresses in scheme 1 and existing bridge are both about 2.85 MPa, and transversal distribution is homogeneous relatively. Equivalent stress of the other four schemes decreases 28%, 9%, 8% and 29% respectively and it changes within 0.20 and 0.75 MPa. It shows that global stiffness of structure has improved after strengthening. In addition, there are sharp angles in distribution curves of equivalent stress. It is mainly because local stiffness increases after strengthening, and concentrated load causes stress concentration.

From figure 9 it is seen that transversal stress at midspan is tension stress, and stress of scheme 2, 3, 4 and 5 decreases 29%, 6%, 5% and 27% respectively. Strengthening effectiveness of adding plate at bottom and transversal prestress is best.
3.2.2. Longitudinal Distribution Rule of Displacement and Stress at Bottom Plate. Figures 10-12 show longitudinal distribution of displacement and stress at bottom plate. Distribution curves of displacement and stress are parabola. The maximum equivalent stresses of existing bridge and strengthening schemes are 2.85 MPa, 2.83 MPa, 2.06 MPa, 2.59 MPa, 2.63 MPa and 2.03 MPa respectively. The maximum transversal tension stresses are 0.58 MPa, 0.58 MPa, 0.43 MPa, 0.54 MPa, 0.53 MPa and 0.42 MPa respectively. Analysing from strengthening effectiveness we can see the
strengthening schemes of adding plate at bottom and transversal prestress is the best and secondly increasing beam height.

![Figure 10. Longitudinal distribution of $f$ at bottom plate.](image)

Figure 10. Longitudinal distribution of $f$ at bottom plate.

![Figure 11. Longitudinal distribution of $\sigma_e$ at bottom plate.](image)

Figure 11. Longitudinal distribution of $\sigma_e$ at bottom plate.

![Figure 12. Longitudinal distribution of transversal stress at bottom plate.](image)

Figure 12. Longitudinal distribution of transversal stress at bottom plate.

Considering from transversal stiffness of structure, scheme 1 adding reinforcements in hinged joints is not available, for the effectiveness of improving stiffness is not obvious, and it is not easy in constructing but it really has some significance in design. Scheme 4 increasing beam height can improve structural stiffness and its construction is easy, but it causes dead weight increasing, and it cannot solve problem thoroughly. Scheme 2 and 3 (adding steel plates) both can improve transversal connection of between plates and structural stiffness, and decrease even avoid single plate bearing. Moreover, construction is convenient. Scheme 5 adding transversal prestress, which has already been used in France, can improve structural stiffness while construction is difficult.

3.2.3. Distribution Rule of Displacement and Stress at Hinged Joints

Figure 13 shows vertical distribution rule of displacement and stress at hinged joints. We can see that transversal stress at upper plate is compression stress, and transversal stress at bottom plate is tension...
stress. Compressive height of existing bridge and scheme 1 and 4 is about 0.12 m, and the maximum tension stress at bottom comes to 0.6 MPa. Compressive height of scheme 2, 3 and 5 is about 0.04 m, and the maximum stress at bottom is only 0.45 MPa, which is 25% less than that of the others. The prime reason is that concrete has poor performance in tension; on contrary steel plate has a good performance in tension, so tensile force is mainly carried by steel plates. The maximum transversal tension stress of scheme 5 is 0.42 MPa because transversal prestress caused transversal stiffness increasing, and at the same time bottom is in compressive state which can neutralize tension stress cause by additional load. We also can see slope coefficient of stress distribution curve is different, which indicates there are differences in the global stiffness of each scheme. As a whole adding steel plate at bottom is the best scheme to increase structure stiffness, which is favour of preventing single plate bearing. Its reason is that bottom is usually in tension state under load, which leads to loose connection of internal structure and it is easy causing fracture, finally structural stiffness decreased. Therefore, it is better to strengthening at bottom than at upper. It can delay or avoid tension stress and improve global stiffness of structure, so the probability of single plate bearing will decrease.

![Graph showing stress distribution](image)

**Figure 13.** Vertical distribution of transversal stress at hinged joints.

In addition, as connection between concrete hollow plate and hinged joints cannot be very close, it is a weak link in itself so when analysing stress at hinged joints we should use adhesive strength at conjunction surface between new and old concrete as evaluating indicator. According to related documentations, tension strength at conjunction surface between new and old concrete is as about 1/3 time as that of concrete and as 0.035 time as axial tension strength [5,11]. The maximum transversal tension stress (shown in figure 13) has already exceeded its tension strength which indicates there must be fracture occurring.

### 4. Conclusions

1. On the same condition, stress has decreased in different degree after strengthening, the best is scheme 5 adding transversal prestress; secondly scheme 2 adding steel plate at bottom; thirdly adding steel plate at upper plate.

2. Each scheme has its unique merit and demerit. We should select proper strengthening schemes according to real characteristics of engineering. Scheme 2 and 3 are commended here. These two schemes not only have obvious strengthening effectiveness but also are easy in construction. Strengthening effectiveness of adding transversal prestress is distinct but construction technology is difficult. However, with the construction technology improving, it will be used in future.

3. It is suggested that the weak link of hinged joints should be considered in design, construction and operation. Measures should be taken to improve transversal stiffness and crack resistance. Construction quality must be ensured. In operation in order to guarantee safe, we must enhance traffic management, meanwhile pay more attention to maintenances.

In addition, conclusions in this paper are obtained from numerical analysis, so they need test and improvement in engineering experiment and practice. Only in this way, will there be an extensive engineering practice prospect.
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