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Investigation of Crack Causes and Structural Limit State Check of Active Hollow Slab Bridge

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Abstract: Aiming at the cracks of the hollow slab bridge in service, a special on-site traffic survey is carried out. Based on the survey, the limit state of the hollow slab bearing capacity is checked, and the internal and external causes of the cracks in the hollow slab are analyzed to provide subsequent reinforcement treatment in accordance with.

Keywords: hollow slab; crack; traffic investigation; limit state check

1. Project Overview

An expressway is an important part of the National Highway Network Plan. There are 170 bridges on this high-speed down line. Except for the K136 + 560 down line which is a 1-180m box-rib arch bridge, the remaining bridges are all 20m and 30m post-tensioned pre-stressed concrete wide hollow slabs. According to the "Regular Inspection Report of Bridge Maintenance for This Section (2017)", the technical status of the downstream bridges on a certain section is shown in Figure 1. Among the 170 bridges on this section, there are 10 Class 1 bridges, accounting for 5.88% of the total number of bridges; There are 60 types of bridges, accounting for 35.29% of the total number of bridges; 80 types of bridges, accounting for 47.06% of the total number of bridges; 20 types of bridges, accounting for 11.76% of the total number of bridges. The technical status of the bridges in this section is rated as Class 3 or 4 bridges, accounting for 58.82% of the total number of bridges in this section, and the bridge is in a serious condition.

Figure 1. Technical status of downlink bridges on a section

2. Disease Growth Trend

Through statistical comparison of the damage conditions of beams and slabs in the inspection reports in 2014, 2016 and 2017, the growth trend of the downward link bridge is shown in Figure 2 and the downward link bridge growth is shown in Figure 3. The main disease of this type of hollow plate is that there are a large number of diagonal shear shown in shown in Figure 3. The main disease of this type of hollow plate is that there are a large number of diagonal shear cracks on the end plate of the plate; there are a large number of transverse bending cracks across the bottom of the middle plate, and it develops from the bottom of the plate to the web and gradually increases year by year. From 2014 to 2017, the proportion of bridge beams and slabs on the descending line of road sections has increased year by year, from 0.85% in 2014 to 20% in 2017. Especially from 2016 to 2017, bridge diseases have developed rapidly. In just one year, the number of diseased beams and slabs as a percentage of the total beams and slabs increased rapidly, by 13 percentage points.

Figure 2. Growth trend of downlink bridge diseases

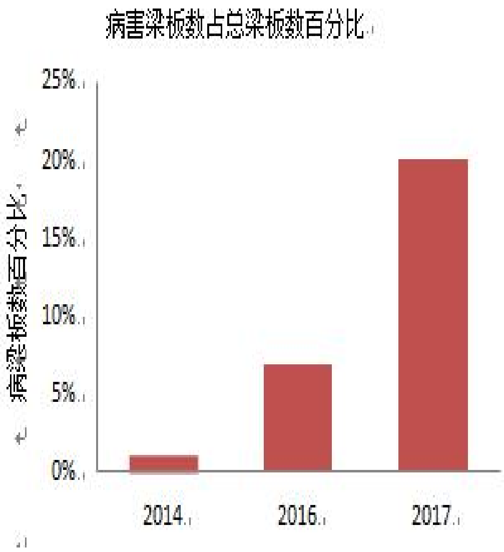

Figure 3. Histogram of downward bridge disease growth

3. Cause Investigation and Analysis

3.1 Traffic investigation and analysis

The traffic survey is to obtain the real data of the movement of the selected points of the vehicle highway system, to understand the temporal and spatial changes and distribution laws of the traffic, and to provide the necessary data for the analysis of the causes of the bridge diseases. The original data of this traffic statistics is based on the statistics of a certain management office of the expressway. The data is shown in Table 1. In the table, the first type is a small passenger car with 1-7 seats (including 7 seats); Including 19 seats) medium-sized passenger cars and small trucks of less than 2 tons (including 2 tons); Type 3: large passenger cars of 20 to 39 seats (including 39 seats) and medium trucks of 2 to 5 tons (including 5 tons); Type: Heavy passenger vehicles with more than 40 seats and large trucks with a capacity of 5 to 10 tons (including 10 tons); Type 5: Heavy trucks with a capacity of 10 to 20 tons (including 20 tons).

Table 1. Summary unit of traffic survey (vehicles)

	Type 1 Car	Type 2 Car	Type 3 Car	Type 4 Car	Type 5 Car	Total	Monthly Average Traffic
January-December 2012	4052960	114975	318280	38325	168265	4692805	391068
Car Model Ratio	86.37%	2.45%	6.78%	0.81%	3.59%	100%	/
January-December 2013	4575640	137605	381060	39055	213890	5347250	445605
Car Model Ratio	85.57%	2.57%	7.13%	0.73%	4.0%	100%	/
January-December 2014	5012897	141690	333245	29930	254770	5772532	481045
Car Model Ratio	86.84%	2.46%	5.77%	0.52%	4.41%	100%	/
January-December 2015	5611510	152570	334705	28470	330690	6457945	538163
Car Model Ratio	86.89%	2.36%	5.19%	0.44%	5.12%	100%	/
January-December 2016	7800780	162425	392375	55480	457345	8868405	739034
Car Model Ratio	87.96%	1.83%	4.42%	0.63%	5.16%	100%	/
January-August 2017	5954610	105120	293460	43557	411720	6808467	851059
Car Model Ratio	87.46%	1.54%	4.31%	0.64%	6.05%	100%	/

The above types of statistics are collected by toll models, and there is a certain deviation from the classification of asphalt pavement design traffic volume models. Based on the collected annual traffic volume of various toll models, the survey converted the toll models of expressways into annual average daily traffic volume with passenger cars as standard models. Combining the five vehicle classification standards for highway toll stations and the highway engineering technical standards (JTJB01-2014) in Table 3.2, each vehicle's representative vehicle types and vehicle conversion coefficients, the toll vehicle type 1 and type 2 conversion factors are approximately 1.0; type 3 The conversion factor for the vehicle representative is approximately 1.5; the conversion factor for Type 4 and Type 5 vehicles is approximately 2.5 [1]. The traffic volume after conversion is shown in Table 2.

Table 2. Annual average daily traffic volume after conversion (unit)

Year	**Total Annual Traffic (Vehicles)**	**Annual Average Daily Traffic Volume (Cars / d ▪ Lane)**
2012（1～12）	5161830	7071
2013（1～12）	5917198	8106
2014（1～12）	6366205	8721
2015（1～12）	7164038	9814
2016（1～12）	9833830	12471

The above results show that the average daily traffic volume per lane from 2012 to 2017 (January to August) increased from 7071 to 15695, and the volume of traffic in 2017 (January to August) increased by 2.22 times that of 2012. It can be seen from the growth trend that the growth rate from 2012 to 2015 is relatively slow, with an average growth rate of 11.6%; from 2015 to 2017 (January to August), the growth rate is relatively fast, with an average growth rate of 26.8%. The growth of traffic volume has a certain correlation with the development of disease. From 2015 to the first half of 2017, the growth rate of traffic volume was high. At the same time, the disease development of bridges during this period was also rapid. The development of bridge diseases is related to the increase in traffic volume and the repeated effects of vehicle loads, which causes the bridge to have certain fatigue damage.

3.2 Analysis of overloaded vehicles

Overloaded vehicles on the highway not only cause disorder in the transportation market order, but also directly cause serious damage to highway bridges and high incidence of traffic accidents, posing a major threat to the lives and property of the people. According to relevant research, the increase in vehicle overload weight and its damage to the road surface has increased geometrically. The overload of a 10% truck will increase the road damage by 40%. A vehicle overloaded twice will run once. The damage to the road is equivalent to 16 times without exceeding the limit. The most damaging is the bridge. Because overloaded vehicles mostly adopt plate springs and other methods, the total load and axle load greatly exceed the design load standards of highway bridges, thus bringing hidden safety hazards to the use of the bridge [2-3] . According to the information provided by the management office, an analysis was performed on the overloaded vehicles exceeding 55 tons from 2015 to 2017 (January to July), and the statistics are shown in Table 3.

Table 3. Units for analysis of over 55 tons weighing vehicles

Project	**Numbers of Vehicles in 2015**	**Numbers of Vehicles in 2016**	**Number of Vehicles from January to July in 2017**
Total	5018	49561	46727
Total Annual Traffic	7164038	9833830	6683349
Ratio	0.07%	0.50%	0.70%

From the above analysis, it can be seen that the expressway is overloaded very severely, and the number of overloaded vehicles is increasing rapidly year by year. From 2015 to 2016, the number of vehicles over 55 tons increased from 5018 to 49561. Overloaded vehicles in just one year It has increased by nearly 10 times; from January to July 2017, the number of vehicles exceeding 55 tons reached 46,727, which is close to the total number of 2016. According to the analysis, from 2015 to 2017, the rapid development of bridge diseases on this line is closely related to the rapid growth of overloaded vehicles. The large increase in overloaded vehicles caused the load effect to be greater than the designed carrying capacity, which caused serious damage to large-scale bridges on the line.

3.3 Bridge disease growth analysis and forecast

According to the change law of the development of bridge diseases on the high-speed downward line from 2014 to 2017, through curve fitting, a model for predicting the growth of bridge diseases can be obtained, which can predict the trend of the development degree of bridge diseases on this road section without effective reinforcement treatment. After fitting, the change trend of the development of the high-speed downlink bridge disease is shown in Figure 4. According to the binomial formula, $y = 0.037 (X-2014) 2-0.051 (X-2014) +0.023$ ($R2 = 1$) Growth: In the formula: X—year; R2—

goodness of fit. The range of R value is [0,1]; y—the number of diseased beam plates as a percentage of the total beam plates. The prediction model of disease development is based on the data of the detection report from 2014 to 2017, and the function of the disease is estimated by curve fitting correction to estimate the development of the disease. The actual growth pattern of the disease may differ from the model prediction.

Figure 4. Forecast of the growth of down-Line bridge diseases

According to the predictive analysis model, it can be obtained that without effective reinforcement treatment, it is expected that by 2018, the number of disease beams and slabs on the high-speed downlink bridge will account for 41.1% of the total number of slabs; by 2019, this proportion will reach 69.3%. According to the prediction model, the development law of bridge diseases will increase at a rate of about 20% after 2016. The development of bridge diseases is not optimistic, so it is imminent to take effective curative measures for bridge diseases on this section.

4. Limit State Check of Bearing Capacity of Wide Hollow Slabs of Typical Disease Bridges

4.1 Overview of wide hollow slabs of typical disease bridges

The downstream bridge was completed and opened to traffic in 2000, and the original bridge design load rating was car-super 20, trailer-120, designed according to 85 specifications. During the 17-year operation period, vehicle traffic increased day by day and was overloaded severely. In order to meet the traffic load of existing vehicles, the Ministry of Communications has promulgated 15 design specifications. During the bridge inspection, it was found that the bridge was severely damaged. It was mainly cracks on the bottom of the hollow slab and cracks on the end web. Hollow slabs are checked for ultimate bearing capacity.

4.2 Checking basis and thinking

According to the above-mentioned traffic survey and analysis, and the description of the down-line bridge diseases, that is, bridges in the fourth and fifth grades of bridge technical conditions, it is urgent to solve the problems of increasing the load level of existing bridges and strengthening treatment or replacing existing beams and plates with serious diseases. According to Article 3.1.1 of the Regulations for Testing and Evaluating the Carrying Capacity of Highway Bridges (JTG / T J21-2011), the bridges in the fourth and fifth categories of technical conditions and the bridges intended to increase the load level shall be subjected to the test and assessment of the load capacity 4]. Therefore, when carrying out the limit state check of the bearing capacity of problem beams and plates, the first consideration should be given to the loading requirements, and the vehicle load rating of 85, the vehicle load rating of 04, and the vehicle load rating of 15 respectively.

Second, the impact of various reduction factors, check coefficients, and deterioration coefficients should be considered and checked [5-6].

4.3 Edge plate analysis

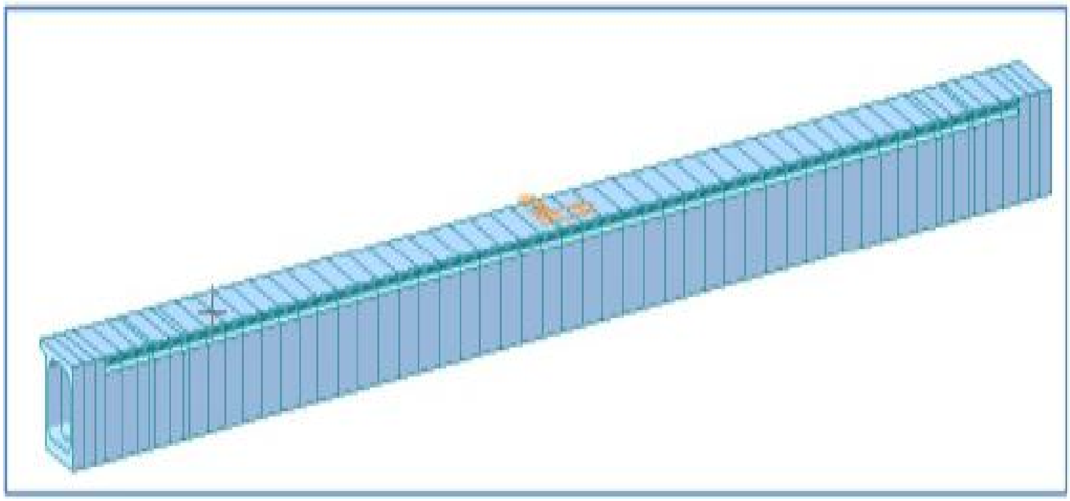

Figure 5. Edge plate finite element model

The finite element model of the edge plate is shown in Figure 5. The finite element analysis of the limit state of the load carrying capacity of the edge plate is shown in Table 4. From the above chart, it can be known that whether it is designed according to the original 85 specifications or according to the existing loading requirements, the limit state of the bearing capacity of the beam and slab edges of the bridge disease has not met the requirements of the bending capacity.

Table 4. Calculation of the limit state of the bearing capacity of the side plate span

Guogao Network Station	**Number**	**Beam Plate Number**	**Check Section**	**Moment Combination Design（kN.m）**			**Corrected Section Bending Resistance（kN.m）**	**Safety Factor**		
				85standard	**04standard**	**15standard**		**85standard**	**04standard**	**15standard**
K137 + 605 Down Line	1	2-6	Mid-Span Section	5037	6260	6486	4697	0.933	0.750	0.724
	2	3-6	Mid-Span Section	5037	6260	6486	4707	0.934	0.752	0.726
	3	4-6	Mid-Span Section	5037	6260	6486	4740	0.941	0.757	0.731
	4	5-6	Mid-Span Section	5037	6260	6486	4524	0.898	0.723	0.698
K137+260 Down Line	5	1-6	Mid-Span Section	5037	6260	6486	4655	0.924	0.744	0.718
	6	3-6	Mid-Span Section	5037	6260	6486	4450	0.883	0.711	0.686
	7	4-6	Mid-Span Section	5037	6260	6486	4599	0.913	0.735	0.709
	8	2-6	Mid-Span Section	5037	6260	6486	4830	0.959	0.772	0.745

4.4 Medium plate theory analysis

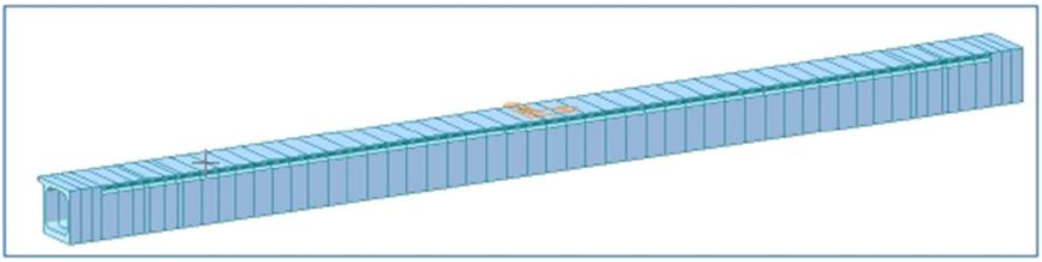

Figure 6. Medium plate finite element model

The medium plate finite element model is shown in Figure 6. The finite state analysis of the limit state of the mid-span carrying capacity is shown in Table 5.

Table 5. Calculation table of limit state of mid-span carrying capacity

Guogao Network Station	**Number**	**Beam Plate Number**	**Check Section**	**Moment Combination Design（kN.m）**			**Corrected Section Bending Resistance（kN.m）**	**Safety Factor**		
				85standard	**04standard**	**15standard**		**85standard**	**04standard**	**15standard**
K137+605 Down Line	1	1-3号	Mid-Span Section	4589	5649	5835	4761	1.037	0.843	0.816
	2	1-4号	Mid-Span Section	4589	5649	5835	4686	1.021	0.830	0.803
K137+260 Down Line	3	2-5号	Mid-Span Section	4589	5649	5835	4655	1.014	0.824	0.798
	4	3-4号	Mid-Span Section	4589	5649	5835	4922	1.073	0.871	0.844

As can be seen from the above table, according to the original 85 specification design, the state of the carrying capacity chassis is still reserved, but the safety reserve is very small. As the cross section deteriorates or the disease worsens, it is eventually consumed. If the load is lifted in accordance with 04 and 15 codes, the limit state of the bearing capacity of the beam and slab in the case of bridge damage does not meet the requirements of the bending capacity. From the figure above, it can be seen that the short-term load combination has a tensile stress of 1.9Mpa at the lower edge of the slab after reduction. The design value of the tensile strength of No. 40 concrete in the Code for Design of Highway Reinforced Concrete and Pre-stressed Concrete Bridges and Culverts (Code 85) is 1.65 Mpa [7], because 1.9Mpa>

1.65Mpa, the through transverse cracks are generated at the bottom of the board, and the normal use limit state cannot meet the existing traffic load requirements.

5. Disease Cause Analysis

5.1 Earlier structural design and lower original code design load level

Because the design load level of the original bridge is car-super 20, hanging -120, the design load level is low, which cannot meet the load level of existing traffic. According to the results of the assessment of the bearing capacity of the above four types of bridge slabs, it can be concluded that the existing beams and slabs no longer meet the requirements of the bearing capacity, and the existing bridges are evaluated according to the 85 standard. If the vehicle load rating is increased according to the 04 and 15 specifications based on traffic analysis, the ultimate limit state of the bending capacity of the hollow slab does not meet the requirements of the specification. Therefore, under the long-term load of the structure, the prestress loss of the bridge causes the concrete tensile stress at the bottom of the slab when the tensile strength of concrete is exceeded, lateral bending cracks appear at the bottom of the slab.

5.2 Dramatic increase in traffic volume and increase in overloaded vehicles

Due to the inadequate estimation of the design traffic in the early design stage and the sharp increase in traffic in recent years, the growth rate of traffic was relatively fast from 2015 to 2017 (January to August), with an average growth rate of 26.8%; and from 2015 to 2016, the number of vehicles exceeding 55 tons increased from 5018 to 49561, and overloaded vehicles increased by nearly 10 times in just one year; from January to July 2017, the number of vehicles exceeding 55 tons reached 46,727. The number of vehicles is close to the whole year of 2016; the large increase in traffic volume and overloaded vehicles results in a load effect greater than the designed bearing capacity, which results in transverse bending cracks. The large-scale cracks are also reflected in the outer side plate and the secondary side plate, so the damage of the overloaded truck to the beam plate cannot be ignored.

5.3 The route is located on a long downhill section, and the car’s impact load exacerbates the structural damage

The high-speed descending line is located on the long downhill section and the bridge surface is uneven. When the vehicle is driving on the long downhill section, it is inevitable that brake braking occurs, especially the frequent braking of heavy and overloaded vehicles, and the unevenness of some bridge surfaces, the bridge produced large shock vibration, which exacerbated the development of bridge cracks.

6. Conclusion

Based on the analysis of the growth of high-speed traffic, overloaded vehicles, and the limit state of the existing hollow slab bearing capacity, the analysis shows that the high-speed hollow slab diseases are mainly caused by internal and external factors: the internal factors are mainly: structural design earlier, according to the original design code, the design load level was too low, and it was difficult to meet the load level of the existing traffic, and the limit state of the bearing capacity of the hollow slab did not meet the requirements of the existing code [8]. The main external factors are: the rapid increase in traffic volume and the rapid increase in overloaded vehicles, which make the load effect greater than the designed bearing capacity of the bridge, resulting in structural stress cracks. The route is located on a long downhill section. Frequent braking of vehicle loads and unevenness of part of the bridge deck cause a large impact load on the bridge, which exacerbates the development of bridge cracks.

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