Study on Measurement Index of Transverse Collaborative Working Performance Based on Prefabricated Girder Bridges

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Abstract. Transverse collaborative working performance during the operation of prefabricated girder bridges is critical to their safety and serviceability. An indirect measurement index, the strain correlation coefficient of adjacent prefabricated girders, is proposed to represent the transverse collaborative working performance. A simplified mechanical model of prefabricated girder bridges is established. Based on this model, an analytical expression of the proposed index is derived. Theoretical analysis and numerical simulations are used to show that traffic flow tends to be statistical stable when using a sufficient sample size, in which case structural characteristics exclusively become the influencing factor of the index. This indicates that the proposed index is capable of accurately reflecting the transverse collaborative working performance of prefabricated girder bridges.

Introduction

Prefabricated girder bridges have numerous desirable features, including simple and efficient construction, a high degree of industrialization, and low costs, making them the most widely used type of bridge. In order to maintain a smooth and safe traffic line, strengthening maintenance and management of prefabricated girder bridges based on monitored working performance is of great significance. During operation, the main risks such as weakening even failure of bridge girder transverse connection structures reflect the health condition of the bridge, and a decline in the transverse collaborative working performance could cause the bridge superstructures to have extremely unfavorable stress states. Therefore, understanding the transverse collaborative working performance of prefabricated girder bridges is critical to its design, management, and maintenance [1].

Existing research regarding prefabricated girder bridges transverse collaborative working performance focuses on the characteristics of transverse load distribution. In 1995, R. E. Abendroth studied the transverse load distribution of T beams with intermediate diaphragms [2]. In 2000, Brett A. McElwain used field response data to study transverse bending distribution factors and dynamic load allowance [3]. Baidar Bakht discovered that the transverse load distribution pattern of a bridge improves by a relatively small margin as the ultimate limit state is approached [4]. Hassan H. Abbas used theoretical, experimental, and finite element analyses to study the flange transverse bending of corrugated web steel I-girders under in-plane loads [5]. In 2012, CHEN Ji-hao presented a method to calculate the influence line of transverse load distributions, applied to any hinge-jointed hollow slab bridge [6]. CHEN Huai analyzed changes in structural displacement and stress, with respect to transverse load distribution, for cases of prefabricated hollow slab bridges subjected to transverse pre-stress, proving that transverse pre-stress can effectively improve transverse load distribution and transverse collaborative working performance [7]. LIN Yang-zi suggested a group of transverse load distribution correction factors that can be applied to precisely measure transverse collaborative working performance of prefabricated girder bridges [8]. In 2011, Liu. H. and Y. Sun suggested a method for computing transverse influence lines of hinge-jointed hollow slab bridges composed of pavement [9]. Transverse load distribution analyses and transverse influence line calculations have been investigated by these research works; however, there is still a lack of information regarding transverse collaborative working performance of prefabricated girder bridges, including an established definition, measurement method, and analysis of the effect of traffic flow.

Transverse collaborative working performance of prefabricated girder bridges plays a crucial role in the overall performance of the bridge; therefore, it is necessary to conduct investigations pertaining to this concept.

Transverse Collaborative Working Performance Measurement Index

The transverse connection stiffness directly reflects the transverse collaborative working performance of a prefabricated girder bridge, but it is difficult to measure because of multi-factor integrated effects. Therefore, stiffness cannot be used as a measurement index of transverse collaborative working performance. As previously mentioned, due to the transverse connection system, the effect of girders depends on the effect of their adjacent girders during the operation period, thereby resulting in a correlation between the proximity of the girders. The transverse connection stiffness of adjacent girders determined the value of their correlations. This means that the effect correlation of the prefabricated girders indirectly reflects the transverse collaborative working performance. In general, strain can be simply measured at all the effects on the bridge, which allows the strain correlation of prefabricated girders to be used in the determination of the transverse collaborative working performance.

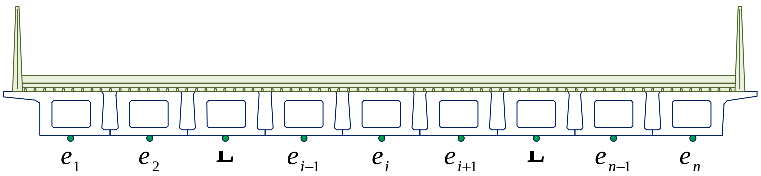


Fig. 1. Prefabricated girders bottom strain of mid-span section

As is shown in Fig. 1, e_i is the girder bottom midpoint longitudinal strain of the i^{th} girder, where $i = 1, 2, \mathbf{L}, n$ and n is the number of girders (girder mid-span section was used as the sensor installation position). Because of the time-varying nature and randomness of traffic flow, e_i was also represented as a time-varying characteristic having an element of randomness during daily operation. A strain data sequence based on time was obtained through continuous observation of strain as follows:

$$\mathbf{E}_i = \{e_{i1}, e_{i2}, \mathbf{L}, \ e_{iL}\} \tag{1}$$

where e_{il} represents i^{th} girder strain of l^{th} observation, $l = 1, 2, \mathbf{L}, L$ and L represents total number of observations

The mid-span section longitudinal strain correlation coefficient of the i^{th} and j^{th} prefabricated girder (hereafter referred to as the correlation coefficient) becomes:

$$r_{ij} = \frac{\text{cov}(\mathbf{E}_i, \mathbf{E}_j)}{\sqrt{D\mathbf{E}_i \cdot D\mathbf{E}_j}} = \frac{E(\mathbf{E}_i \mathbf{E}_j^{\ T}) - E(\mathbf{E}_i)E(\mathbf{E}_j)}{\sqrt{E(\mathbf{E}_i - E(\mathbf{E}_i))^2 E(\mathbf{E}_j - E(\mathbf{E}_j))^2}} \tag{2}$$

Here, the correlation coefficient r_{ij} represents the correlation between the mid-span section longitudinal strain of the i^{th} and j^{th} prefabricated girders, where $j = 1, 2, \mathbf{L}, n$, $i \neq j$. This equation represents the transverse connection performance of prefabricated girders, and can be calculated by simply measured strain data; therefore, it meets the basic requirements of representing transverse collaborative working performance of prefabricated girder bridges.

Random Traffic Flow Model and Numerical Simulation Method

Random Traffic Flow Model. Traffic flow is affected by many factors including time, regional road network layout, transportation planning, traffic laws, and regional economics amongst others, and is therefore highly variable; however, there is statistical stability when using longer measurement times. The fact that traffic flow statistical characteristics of different road routes and segment of the same road route are individually varied should be taken into consideration [10].

The basic unit of traffic load is vehicle load, though different vehicle models have different mechanical effects on a bridge. In a statistical sense, regarding moving vehicles as concentrated forces not only helps grasp the principal part of traffic load, but also provides a convenient approach to performing mechanical analysis from the overall bridge view. Based on this research, parameters including the probability of vehicles moving on a bridge, vehicle weight, vehicle speed, and transverse position within a vehicle lane can be extracted from the traffic flow model. The individuality of the characteristics of traffic flow is reflected in the similarities and differences of distribution patterns and distribution parameters of these four random variables.

Vehicles moving on a bridge can be simulated by the Poisson distribution, a binomial distribution, or a negative binomial distribution. The Poisson distribution is applied to scenarios of low traffic density, weak interaction of vehicles, and minimal existence of external interference factors. The binomial distribution is applied to scenarios of heavy traffic excluding free travel. The negative binomial distribution is applied to scenarios having high volatility of arriving vehicles [11]. For long-term strain observation, random traffic stream, weak interaction of vehicles, and low presence other external interference factors were assumed, so the Poisson distribution was correspondingly applied. The probability density function of Poisson distribution is described by the following formula:

$$f(x) = \frac{l^x}{x!} e^{-l} \quad (x = 0, 1, 2, \cdots, \infty) \tag{3}$$

where x represents the number of arriving vehicles and l represents the average number of vehicles arriving per unit time.

Recent research demonstrates that vehicle weight can be applied using a normal distribution, lognormal distribution, exponential distribution, Gamma distribution, Weibull distribution, extreme value distribution, or multi-peaks distribution [12].

The distribution patterns of vehicle speed are usually obtained through vehicle speed observation [13], including normal distribution, Gamma distribution, Weibull distribution, and Logistic distribution, amongst others, that are used to describe the randomness of speed [14]. This study used a normal distribution to describe vehicle speed, consistent with recent research.

From investigation of wheel trajectory transverse distribution data it could be concluded that the distribution of lane transverse position of most vehicles conforms to a normal distribution [15]. For this calculation, the vehicle load was simplified to be a concentrated force in the study so that the distribution of lane transverse position of vehicles could be assumed to conform to a normal distribution.

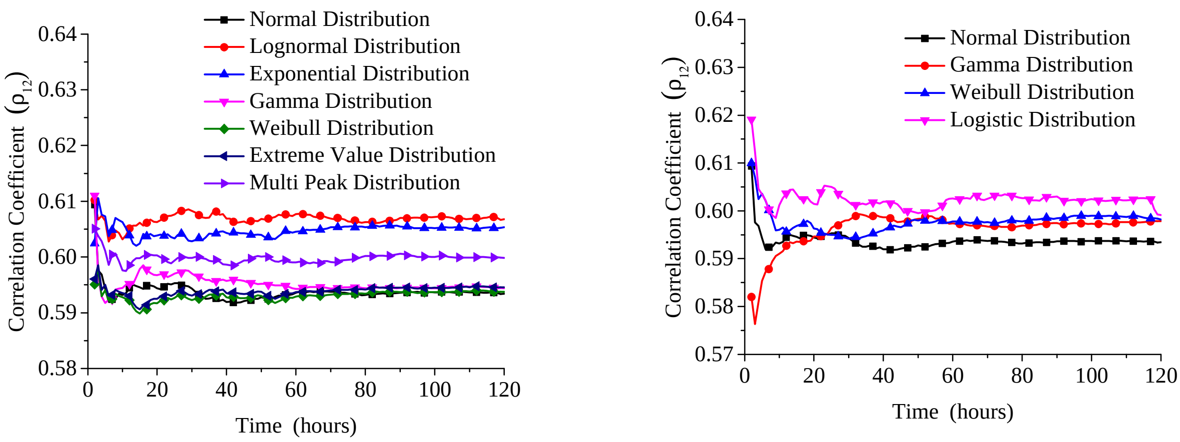
Numerical Simulation Method. The numerical simulation was carried out as follows: (1) generate random vehicles, including information of lane transverse position of vehicle, longitudinal position, vehicle weight, vehicle speed, and time; (2) update vehicle information on the bridge when the vehicles move on the bridge, checking whether or not the vehicle is off the bridge by the longitudinal position of vehicle on the bridge, and delete the vehicle if the vehicle is off the bridge; (3) calculate the total strain caused by all the vehicles on the bridge; (4) calculate the correlation coefficient, while continually generating vehicles the strain is steady.

Numerical Simulation Results

Effect of Model Distribution Patterns on the Correlation Coefficient. As previously mentioned, the individualized characteristics of traffic flow model reflects the similarities and differences of parameter distribution patterns and distribution parameter values. Different distribution patterns of the traffic flow model directly influence the value of the correlation coefficient. Therefore, multiple distribution patterns of vehicle weight and vehicle speed were specifically observed, while vehicle movement on the bridge and vehicle transverse distribution positions were fixed, to respectively conform to the Poisson and normal distributions.

The correlation coefficient change curves of different distribution patterns of different parameters with increasing time duration or sample size are shown in Fig. 2. Fig. 2(a) depicts the case of varied distribution patterns of vehicle weight, including normal distribution, lognormal distribution, exponential distribution, Gamma distribution, Weibull distribution, extreme value distribution, and three-peak distribution. Influence curves of vehicle speed distribution patterns on the correlation coefficient are shown in Fig. 2(b), considering normal distribution, Gamma distribution, Weibull distribution, and logistic distribution.

From Fig. 2, a difference in correlation coefficient can be observed when parameter distribution patterns of the traffic flow model are different. When vehicle weight conforms to the extreme value distribution, Weibull distribution, and normal distribution, the difference in the correlation coefficient is small and three curves overlap after give time, but the difference in the correlation coefficients of the three-peak distribution, exponential distribution, and lognormal distribution was substantial. The minimum correlation coefficient occurred when vehicle speed conformed to a normal distribution and the correlation coefficient was slightly greater with higher volatility when it conformed to logistic distribution.



(a) Vehicle weight (b) Vehicle speed

Fig. 2. The influence of different distribution patterns of traffic flow parameters on correlation coefficient r_{12}

The Influence of Distribution Pattern Parameters on the Correlation Coefficient. When the distribution pattern is fixed, the other factors affecting the traffic flow model are the parameters of the probability density function of random variables. According to recent research, vehicles moving on bridge are best characterized by the Poisson distribution, vehicle weight is best characterized by the three-peak distribution, and vehicle speed and vehicle transverse position are best characterized by a normal distribution. Due to space constraints, the scope of this study was limited to the influence of the Poisson distribution parameter l (of vehicles moving on the bridge) and the three-peak distribution parameters (of vehicle weight) on the correlation coefficient.

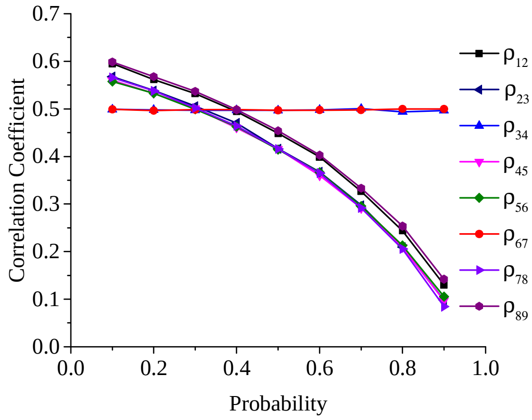


Fig. 3. The relationship of correlation coefficient and probability of generating vehicles

The curves depicting the influence of Poisson distribution parameter l of vehicles moving on bridge on the correlation coefficient are shown in Fig. 3. Here, it can be seen that excluding r_{34}, r_{67} (adjacent girders of adjacent lanes), the correlation coefficient decreased as l increased, while the correlation coefficient of adjacent lanes remained constant.

Conclusions

The theoretical analysis and numerical simulation results indicate that the longitudinal strain effect correlation coefficient of girders' monitoring section is affected not only by the structural inherent characteristic of transverse connection stiffness, but also the statistical characteristics of traffic flow. The correlation coefficient, with sufficient sample length, statistically stabilizes to a specific value when the traffic flow of prefabricated girder bridge also has statistically stable characteristics. Because this index was not affected by single vehicle loads or fluctuation in short time traffic loads, the structural characteristic parameters become the only influencing factor and the correlation coefficient meets the requirement of representing transverse collaborative working performance of prefabricated girder bridges.

The simulation analysis of prefabricated girder bridges using the traffic flow model revealed that the individual traffic flow model has a significant influence on the statistical stable value of the correlation coefficient. Furthermore, the correlation coefficient, even identical girders of factory construction, varies between highway routes. On one hand, this means that a specific correlation coefficient must be used for a specific bridge when representing the transverse collaborative working performance of a prefabricated girder bridge. On the other hand, for identical prefabricated girder bridges of the same road, sharing the same structural parameters and traffic flow trends, a transverse collaborative working performance index measured from one bridge can be applied to other bridges, which provides the theoretical basis for bridge network-based management.

Acknowledgements

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