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Journal of Architectural Environment & Structural Engineering Research
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ARTICLE

Time-varying Reliability Analysis of Long-span Continuous Rigid Frame bridge under Cantilever Construction Stage based on the Monitored Strain Data

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ARTICLE INFO

Article history
Received: 28 March 2019
Accepted: 14 April 2019
Published Online: 30 April 2020

Keywords:
Continuous rigid frame bridge
Structural health monitoring
Construction stage
Punctiform time-varying reliability
Strain data preprocessing

ABSTRACT

In general, the material properties, loads, resistance of the prestressed concrete continuous rigid frame bridge in different construction stages are time-varying. So, it is essential to monitor the internal force state when the bridge is in construction. Among them, how to assess the safety is one of the challenges. As the continuous monitoring over a long-term period can increase the reliability of the assessment, so, based on a large number of monitored strain data collected from the structural health monitoring system (SHMS) during construction, a calculation method of the punctiform time-varying reliability is proposed in this paper to evaluate the stress state of this type bridge in cantilever construction stage by using the basic reliability theory. At the same time, the optimal stress distribution function in the bridge mid-span base plate is determined when the bridge is closed. This method can provide basis and direction for the internal force control of this type bridge in construction process. So, it can reduce the bridge safety and quality accidents in construction stages.

1. Introduction

During the construction of bridge engineering, quality accidents have occurred sometimes. For example, two collapse accidents happened on Quebec Bridge during construction in Canada, of which the span is 548.46 meters. Therefore, monitoring and controlling of the bridge from the beginning of construction is an important methodology to ensure the bridge construction safety and quality, especially the long-span bridges. Today, construction monitoring is an essential part of the modern large-span bridges in the construction stage, and its role is to ensure the safety evaluation for the construction quality and safety of the bridge. Because of the influence of many factors (such as: non uniformity of the material itself, non stability of material properties, the changing of temperature and humidity etc.) and the changing of structure shape, loads and resistance in the construction stage, it makes the internal force safety assessment by the monitoring information of the continuous rigid frame bridge become the difficult parts.

At present, many international scholars have done a lot of research on the theory of engineering structure re-

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DOI: https://doi.org/10.30564/jaeser.v3i1.1779

liability assessment during construction, and the achievement is widely used. Ayyub [1-2] analyzed the cause of the collapse accident of a cast-in-place reinforced concrete structure in Florida beach by the reliability evaluation method during construction period, and puts forward the basic method for structural reliability analysis during construction phase of the project. EI-shahhat, Rosowsky and Chen [3-4] did the structural reliability analysis by using the improved structure analysis method in construction period and the computer numerical simulation method. Yuji Niihara [5] studied the reliability of the prestressed cable stayed bridge during cantilever construction under the condition of wind vibration. Casus [6] suggested a set of partial safety factors for component stability design of the prestressed concrete bridges during cantilever construction. Animesh and Mahadevan [7] et al. proposed a numerical simulation technology of the time-varying load and resistance, and calculate the structural reliability by this method, of which the practicability and accuracy of the method are verified by examples. The document [8] established the reinforced concrete structure resistance and load effects probabilistic models according to the characteristic during construction stage. K.J.M. etc [9] suggested using the normal probability distribution to describe the distribution characters of the monitored stress data got from the SHMS of long-span bridges, and applied the reliability theory to evaluate the safety based on the monitored data. Degtyarev [10] presented a reliability-based evaluation method of the CSSBI 12M provisions for composite steel deck in the construction stage. Liu Yang etc [11] did some theoretical research of reliability calculation of the prestressed concrete continuous rigid frame bridge by the use of MC method in construction stage.

However, it is still lack of the research of reliability assessment method for the cantilever casting concrete bridges based on the monitored data during construction stage, and that it is mainly lack of safety evaluation on the stress state in the phase of the construction and the safety level judgment basis of the stress state when the bridge is closed. So, it is lack of the internal force controlling and regulating basis of this type bridge during construction. Therefore, based on the monitored strain data from the monitoring system of a continuous rigid frame bridge during construction, a safety assessment method is proposed to evaluate the stress state of the continuous rigid frame bridge from the beginning of the construction stage to the bridge closure construction. This method can be used to evaluate the internal force state in each construction stage, and it can ensure the optimal security level of the internal force state of this type bridge when the bridge is in closure construction.

2. Illustration of the Health Monitoring System

2.1 Monitoring of the Strain Data during Construction Stage

The sensors applied to bridge monitoring and test from construction to operation are mainly resistance strain gauge, vibrating wire strain gauge and optical fiber strain sensor etc. As for the strain data records, we use the automation comprehensive test system, which is a powerful distributed automatic static network data acquisition system and adaptive to various automatic engineering monitoring spots, and it can be widely used in engineering field environment monitoring with long time unattended automatic test, such as bridge construction, water conservancy, hydroelectric power, railway, dam, highway etc.

In this manuscript, the strain monitoring during the bridge construction is implemented by JMZX-215 intelligent string type digital strain gauge, which is a kind of embedded concrete strain gauge and capable of simultaneous measurement of strain and temperature, and is adapt to various concrete structure internal strain measurement, long-term monitoring and automatic measurement. The parameters of JMZX-215 type strain gauge are shown in Table 1. The strain gauge installation adopts binding method, and then the strain measurement is carried out after the casting concrete is solidified. Figure 1 is the picture of JMZX-215 string type digital strain embedded in the bridge before casting. Sensors are embedded in the bridge's key sections, and the embedded positions are shown in Figure 2. The cross sections with the measuring points of the health monitoring system in the bridge girder locate near piers, in mid-span and in 1/4 span, and there are total 20 sections (seen in Figure 3). By the adopted system and sensors, the bridge can be monitored in real-time in the construction stage. The data acquisition frequency is one hour.

Table 1. Basic performance parameters of JMZX-215 type strain gauge

Name	Range	Sensitivity	Gauge length	Remarks
Intelligent digital vibrating strain gauge	±1500 $\mu\varepsilon$	1 $\mu\varepsilon$	157 mm	Strain gauge embedded in concrete

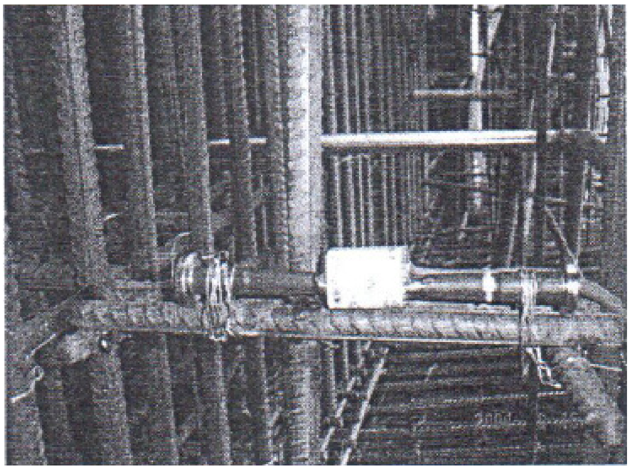

Figure 1. JMZX-215 intelligent string-type digital strain gauge installed inside the bridge before casting

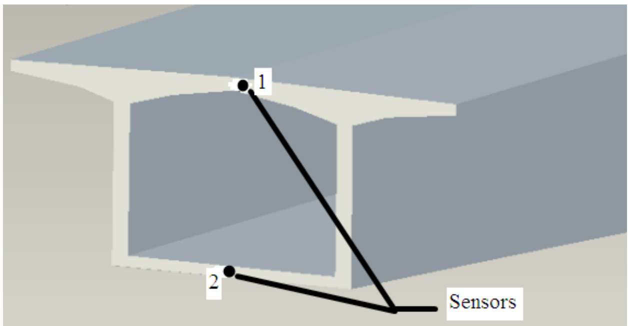

Figure 2. Positions of the embedded sensors in the bridge cross-section

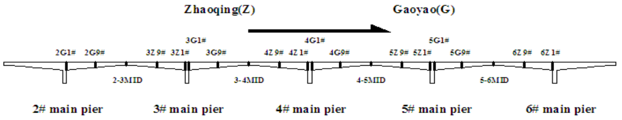

Figure 3. Section locations of the embeded sensors in the bridge girder

2.2 The Initial Monitored Data

The bridge construction was started in 2003 September, closed in June 2005, and was opened to traffic in October 2005. Here, the data collected from the sensors named 4G1-1, 4G1-2, 4-5MID-1 and 4-5MID-2 located near the roots and mid-span between the main pier 4# and 5# are selected as analysis examples, of which the selected monitoring time section is from the bridge 0# block construction (2004 August) to the bridge closure construction, and the time is before opening to traffic (2005 September). Figure 4 shows the shape of the original data collected in the time range from each segmental box girder construction to the bridge finishing.

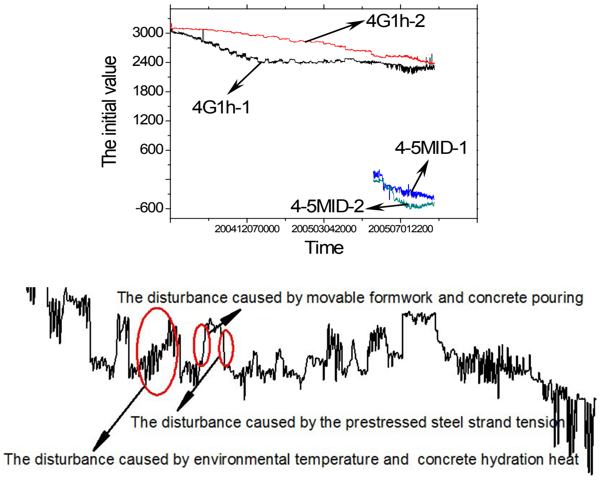

Figure 4. The data profile collected from the bridge SHMS during construction

3. The Main Idea of Punctiform Time-varying Reliability Calculation based on the Monitored Strain Data

3.1 The Reliability Calculation Method

There are many kinds of methods to compute the reliability, such as: the center point method, the first-order second-moment method, the checking point method (JC method), the geometric method, the Monte Carlo numerical method etc. As the reliability calculation by using first-order second-moment method is simple, and its calculation accuracy can meet the requirement of engineering. In the following, this paper uses the first-order second-moment method to solve the practical engineering reliability calculation problem in construction stages. However, the solving result by this method is accurate only if the random variables statistic is independent and obey the normal distribution, otherwise it can only get approximate results.

The resistance $R(t)$ and load effects $S(t)$ of large-span prestressed concrete bridges in cantilever casting construction are both functions of time. As the prestressed concrete bridge cantilever casting is carried out according to construction stage sequence, the function of each construction stage can be expressed as:

$$Z_i(t) = R_i(t) - S_i(t) \qquad (i \in [1, N]) \tag{1}$$

In the formula: N is the number of construction stage experienced by the structural member; i expresses the *ith* construction stage. In the above equation, the function expressed by Eq. (1) is the whole of random process with parameter t, and it is complex to calculate the reliability

DOI: https://doi.org/10.30564/jaeser.v3i1.1779

directly according to the above equation. Therefore, this article uses the structural dynamic reliability analysis method to calculate the reliability, which can take dynamic reliability analysis of structure construction whole process as a collection of static reliability of each construction stage.

In this article, the basic theory of structural reliability calculation is adopted to calculate the bridge component reliability index under each construction stage, and the failure probability P_{fi} of the bridge structure members during each construction stage (or reliability β_i) can be written as [9]:

$$P_{fi} = \iint_{r-s<0} f_{Ri}(r) f_{si}(s) drds \qquad (i \in [1, N]) \qquad (2)$$

In the formula: the meanings of N and i are the same as the above; $f_{ri}(r)$and $f_{si}(s)$are the probability density function of the random variable R of component resistance and load effects S in each construction stage respectively. If $f_{ri}(r)$ and $f_{si}(s)$ both obey normal distribution respectively, the calculation formula of reliability index β_i in each construction stage can be written as:

$$\beta_i = -\Phi^{-1}(P_{fi}) = (\mu_{Ri} - \mu_{Si}) / (\sigma_{Ri}^2 + \sigma_{Si}^2)^{1/2} \qquad (3)$$

In the formula: Φ^{-1} is the inverse function of the standard normal distribution; μ_{Ri} and μ_{Si} are the mean of the resistance and load effects respectively in the bridge's each construction stage; $\sigma_{Ri}$and σ_{Si} are the resistance standard deviation and load effects standard deviation respectively in each construction stage, of which the load effects can be obtained by the internal force monitoring in construction. As the applied stresses and stress capacities both are dependent on concrete material properties, and the correlation between the applied stresses and stress capacities is basically independent. So, we use the material strength as the resistance R in this paper.

3.2 The Probability Density Function of the Structural Resistance

The concrete material strength probability distribution function is taken as the probability density function of the resistance R, which generally obey the Gauss distribution. As the tensile and compressive properties of the concrete are different, two equations are adopted to represent the compressive and tensile strength distribution function:

$$f_{Rci}(r) = \frac{1}{\sqrt{2\pi}\sigma_{ci}} e^{-\frac{(r-\mu_{ci})^2}{2\sigma_{ci}^2}} \qquad (4a)$$

$$f_{Rti}(r) = \frac{1}{\sqrt{2\pi}\sigma_{ti}} e^{-\frac{(r-\mu_{ti})^2}{2\sigma_{ti}^2}} \qquad (4b)$$

In the formula: $f_{Rci}(r)$ and $f_{Rti}(r)$ are the Gauss distribution function of the compressive and tensile strength of concrete respectively in each bridge construction stage; μ_{ci} is the mean compressive strength of concrete material in each bridge construction stage; σ^2_{ci} is the variance of the compressive strength of concrete material in each bridge construction stage; μ_{ti} is the mean of the tensile strength of concrete material in each construction stage; σ^2_{ti} is the variance of the tensile strength of concrete material in each construction stage.

However, the concrete strength changes with time [12]. Zhang Jianren [13] has carried out experimental study on the early change law of the compressive strength and elastic modulus of concrete, and acquired the mechanical property and change law of early strength and modulus of different strength grade concrete , and its strength in different time section can still be assumed to obey normal distribution. As for the strength grade C50 concrete used in the bridge, its cubic compressive strength time-varying model is:

$$\begin{cases} u_{fcu}(\mathrm{t}) = u_{fcu0} \bullet \eta(\mathrm{t}) = u_{fcu0}[\exp(-1.3/\mathrm{t})] \\ \sigma_{fcu}(\mathrm{t}) = \sigma_{fcu0} \bullet \zeta(\mathrm{t}) = \sigma_{fcu0}[(0.1189 + 0.0475t)/\mathrm{t}] \end{cases} \qquad (5)$$

In the formula: μ_{fcu0} and σ_{fcu0} are the mean and standard deviation of 28 days curing compressive strength of concrete cubes; $\mu_{fcu}(t)$ and $\sigma_{fcu}(t)$ are the mean and standard deviation variation of concrete cube compressive strength after t days. For the cantilever casting prestressed concrete bridge which adopts C50 strength grade concrete, Eq. (5) can be used to estimate the mean and standard deviation of concrete axial compressive strength in each construction stage. Among them μ_{fcu0} and σ_{fcu0} can be got by in-situ test.

As we lack field test data of concrete tensile strength parameters, so, we estimate them theoretically. According to the specification [14], there is a approximate relationship between the mean axial tensile strength of the concrete used in the bridge member and the mean standard cube compressive strength. So, we use the following formula to calculate the mean axial tensile strength of concrete material.

$$\mu_{ft} = 0.88 \times 0.395 \mu_{f150}^{0.55} \qquad (6)$$

As for the variation law of C50 concrete tensile

DOI: https://doi.org/10.30564/jaeser.v3i1.1779

strength in construction stage, combined type (5) and (6), this article assumes that it obeys the following changes:

$$\begin{cases} u_t(\mathrm{t}) = u_{t0} \bullet \eta(\mathrm{t})^{0.55} = u_{t0}[\exp(-1.3/\mathrm{t})]^{0.55} \\ \sigma_t(\mathrm{t}) = \sigma_{t0} \bullet \zeta(\mathrm{t}) = \sigma_{t0}[(0.1189+0.0475t)/\mathrm{t}] \end{cases} \tag{7}$$

In the formula: μ_{t0} and σ_{t0} are the mean and standard deviation of the concrete cube tensile strength after 28 days curing; $\mu_t(t)$ and $\sigma_t(t)$ are the mean and standard deviation variation equation of concrete cube tensile strength after t days. So, Eq. (7) is used to estimate the mean μ_{ti} and the deviation $\sigma_t(t)$ of the concrete axial tensile strength in each construction stage in this paper.

On the above, it has been written that the mean compressive strength μ_{fcu0} can be obtained by in situ test. Then, the concrete member axial tensile strength μ_{t0} is estimated by the above Eq. (7) in each bridge construction stage. Also, according to the variation coefficient δ_f in specification [14], which suggests taking the value 0.11, then, standard deviation σ_{t0} of the axial tensile strength of concrete can be estimated. So, the mean and standard deviation of the concrete tensile strength are got, seen in Table 2. Of course, there are uncertainties in the variation of the tensile capacity of concrete applied in this paper and can be eliminated by field test data.

Table 2. The mean and standard deviation of the concrete compressive and tensile strength

Strength	Mean (MPa)	Standard deviation (MPa)
compressive	55.12	6.063
tensile	3.2783	0.361

3.3 Structural Load Effects Probability Density Function

Generally, the bridge load effects probability density function also obeys normal distribution [9]. So, this paper assumes that the load effects probability density function in each concrete bridge construction stage can be expressed as the following formula:

$$f_{Si}(s) = \frac{1}{\sqrt{2\pi}\sigma_{si}} e^{-\frac{(s-\mu_{si})^2}{2\sigma_{si}^2}} \tag{8}$$

In the formula: $f_{Si}(s)$ is the Gauss distribution function of the concrete member load effects in each bridge construction stage; μ_{si} is the mean of component load effects in each bridge construction stage; σ^2_{si} is the variance of component load effects in each bridge construction stage.

According to the previous discussion, if the resistance and load effects of the bridge in each construction stage are both obey normal distribution, Then, the reliability of the concrete bridge in each construction stage can be calculated according to Eq. (3).

As the bridge member resistance has two probability density functions $f_{Rci}(r)$ and $f_{Rci}(r)$ in each construction stage, therefore, according to Eq. (2), there are two reliability indexes β_{ci} and β_{ti} responding to the load probability density function $f_{si}(s)$ in each construction stage. In view of this, the calculation method of the above two reliability indexes in this paper is: if there is $|\mu_{si}-\mu_{ci}|<|\mu_{si}-\mu_{ti}|$, calculate reliability index β_{ci} according to Eq. (2); if not, then, calculate the reliability index β_{ti}, of which the meaning is that the load stress distribution is gradually close to concrete compressive or tensile strength distribution with time and so there is no need to consider the difference in variance, shown in the calculation diagram below.

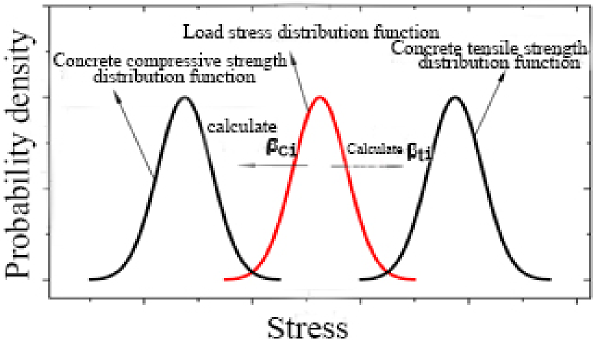

Figure 5. Reliability index calculation schematic diagram of the bridge in each construction stage

4. Preprocessing of the Strain Data

4.1 The Step of the Preprocessing

As the monitored strain can not be directly used for reliability calculation, it must be carried on some necessary preprocessing to transform into stress, and then can be used to calculate the reliability. The steps are as follows:

(1) Take the sensor initial settings after the casted concrete is solidified. Because the sensors are embedded before the concrete casting, the concrete hydration heat will produce initial strain in sensors. So, the monitored strain of each sensor should be subtracted from this value, of which the goal is to get setting values of the sensors after the concrete is solidified.

(2) Subtract the shrinkage and creep strain values from the sensor monitored strain. According to the finite element technology (For example, use finite element calculation software), we build a simulation model of the

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background bridge according to each construction stage, and modify the finite element model by the field test data. Then, based on the FEM model of the bridge, we calculate and extract the shrinkage and creep values corresponding to the embedded strain sensor position in each construction stage. Then, we subtract the extracted shrinkage and creep values from the sensor measured strain values.

(3) Subtract the thermal expansion strain from the sensor monitored strain. Due to the variation of environmental temperature, the monitored strain includes thermal strain. It is best to choose temperature digital strain senor, as mentioned above, which can simultaneously monitor temperature. So, it is easy to remove the thermal strain from the monitored strain.

As the bridge is in construction and not come into service, so, we assume that the measured stains are linearly related to the stresses in this paper and that the concrete material is in linear elastic deformation stage. When the monitored data is processed according to the above method, the stress data can be conversed from the strain data by the following formula:

$$\sigma = E(t) \bullet \varepsilon \tag{9}$$

In the formula: $E(t)$ is the concrete time-varying elastic modulus. During the construction period, the early phase strength and modulus of concrete are changing with time. As the bridge adopts C50 grade concrete, according to the reference [8], the early stage modulus variation law of C50 concrete can be approximately expressed as the following formula:

$$E(t) = E_0(t) \bullet \exp(-0.3/t) \tag{10}$$

In the formula: $E_0(t)$ is the initial modulus after 28 days curing of the concrete, and $E_0(t)$can be got by in situ test. Due to the randomness of concrete materials, Eq. (10) should be revised by measured data. However, due to lacking field test data, we use Eq. (10) to get the approximate values in this paper.

4.2 The Building of FEM Model for Simulating the Bridge Construction

4.2.1 The building of FEM model

In order to deduct the shrinkage and creep effects, this paper uses 3-D finite element program to establish numerical model according to the specific construction process of the bridge (seen in Figure 6). The shrinkage and creep models adopt CEB-FIP 90 model [15], and the material parameters are determined by field measurement, and revise the stiffness coefficient EI according to the deflection monitored data. The model defines 28 construction stages based on the construction process, seen in Table 3.

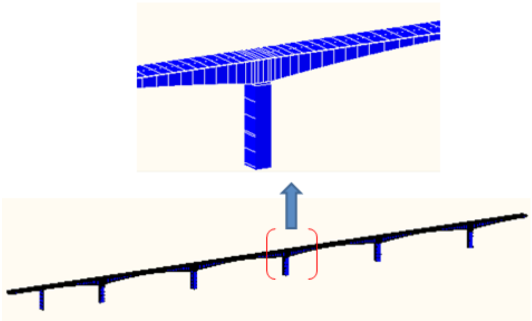


Figure 6. FE model

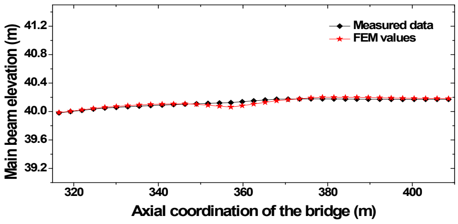
Table 3. Definition of construction phase of the FE model

Stage	Describe
Stage 1	construction of the pier body
Stage 2	construction of block 0# and 1#
Stage 3	construction of block 2#
Stage 4	construction of block 3#
Stage 5	construction of block 4#
Stage 6	construction of block 5#
Stage 7	construction of block 6#
Stage 8	construction of block 7#
Stage 9	construction of block 8#
Stage 10	construction of block 9#
Stage 11	construction of block 10#
Stage 12	construction of block 11#
Stage 13	construction of block 12#
Stage 14	construction of block 13#
Stage 15	construction of block 14#
Stage 16	construction of block 15#
Stage 17	construction of block 16#
Stage 18	construction of the pier 1#
Stage 19	casting of side span
Stage 20	closure counterweight
Stage 21	closure of the secondary side span
Stage 22	Removal of cast-in-place support and hanger
Stage 23	closure of the side span
Stage 24	removal of secondary side span closure segment hanger and bracket
Stage 25	closure of the mid span
Stage 26	removal of mid span closure segment hanger and bracket
Stage 27	bearing transformation of 2# and 6# piers
Stage 28	application of the dead load

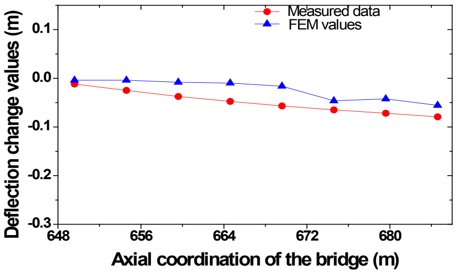
Through calculation, the creep and shrinkage values around the embedded sensors can be acquired.

4.2.2 The Verification of the FEM Model

In order to check the reliability of the finite element model, a calibration work has been done by using the measured elevation data. Figure 7 shows the comparison of part of the main beam elevation and deflection changes between the FE modal and the measured data during construction. Through comparison, the calculation models are basically in line with the reality. So, The FEM model built in this paper can be used to calculate the concrete shrinkage and creep strain values of the bridge.



(a) The main beam elevation



(b) Deflection changes of the main beam

Figure 7. Comparison of part of the main beam elevation and deflection during construction process

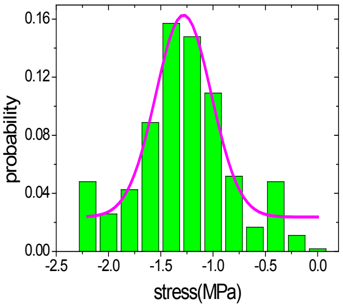
4.3 Division of Statistical Data Time Segment

According to the characteristics of the bridge construction phase, in this paper, we take each construction stage as the statistical time period (The construction stage division is detail described in Table 3). The sample capacity of each statistical segment is about 200 ~ 600, which is enough for load effects statistics, and the derived load effects include the influence of environmental temperature (include extreme weather), the structure shape, live load and resistance changing with time during the bridge construction etc. Each statistical time section is named in the sequence: 0#, 1#, 2#, 3#, 4#, 5#, 6#, 7# 8#, 9#, 10#, 11#, 12#, 13#, 14#, 15#, 16#, 17#, 18#, 19#. Among them, 0 ~ 16# indicate each segmental concrete pouring construction, 17# corresponding to the closure construction, 18# corresponding to the dead load construction, 19# corresponding to the time section from the bridge finished to the time before the bridge opening to traffic.

As the reliability calculated by the above proposed method only reflects the local reliability state and the time-varying characters around the embedded sensors, so, we call this punctiform time-varying reliability.

4.4 Example Analysis

In this paper, we take the data collected from the sensor named 4G1h-1 and 4-5MID-2 embedded in the supporting base top plate and the mid-span section base plate between 4# and 5# pier of the bridge as example, and preprocess the data according to the method suggested in Section 4.1, and convert the data into stress data, and then do statistical analysis of the stress data. Seen from Figure 8 and Figure 9, the stress data are basically normally distributed, but still appear some randomly truncated on the left or on the right, for which the main reason is that there are too many influence factors when the bridge is in construction. In this article, we assume that all the variables are normally distributed and deal with the statistical data by Gauss distribution fitting, which can be seen in Figure 8 and Figure 9. The mean and standard deviation are obtained and shown in Table 4.



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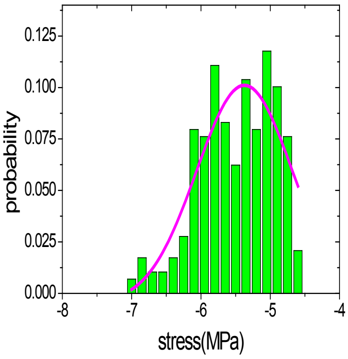

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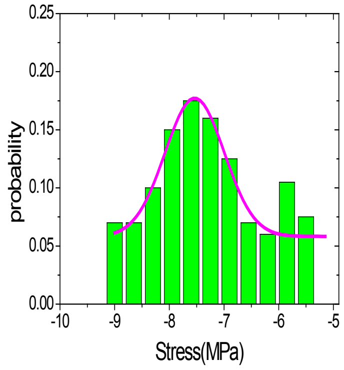

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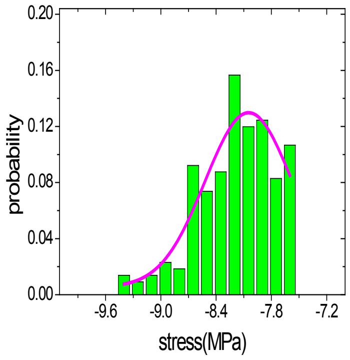

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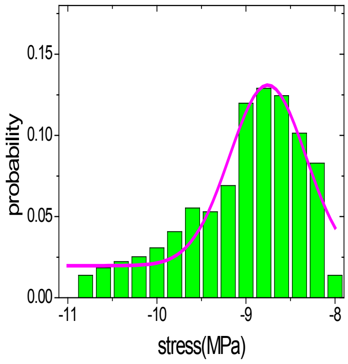

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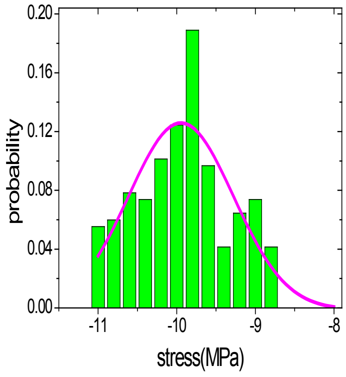

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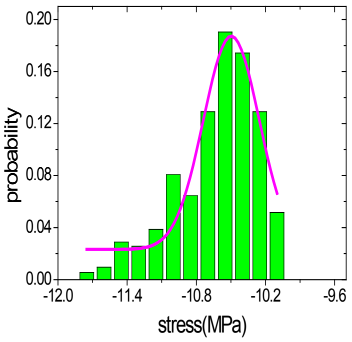

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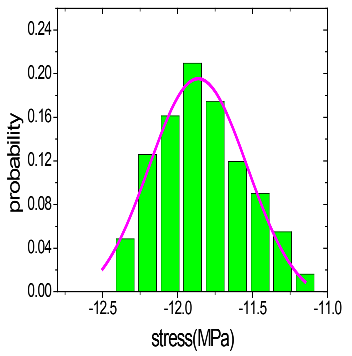

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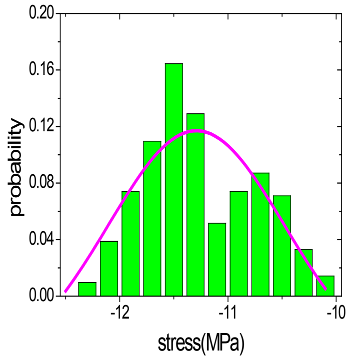
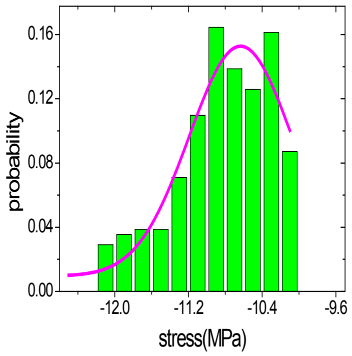
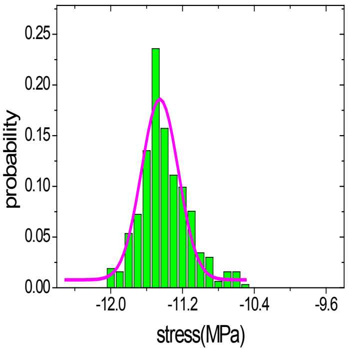


(9#)20041228 ～ 20050108



(10#)20050108 ～ 20050118

DOI: https://doi.org/10.30564/jaeser.v3i1.1779



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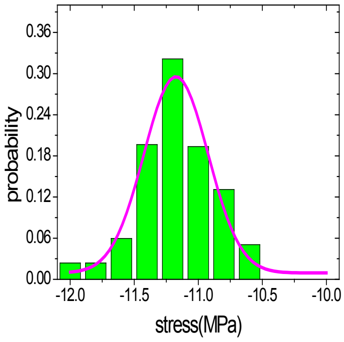

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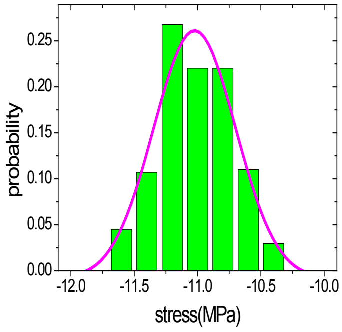

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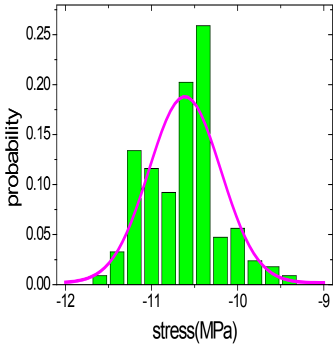

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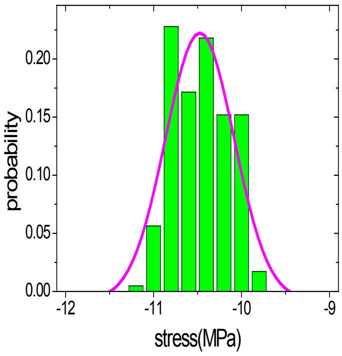

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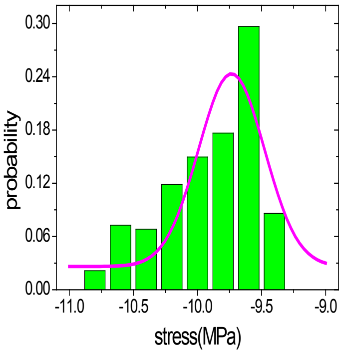

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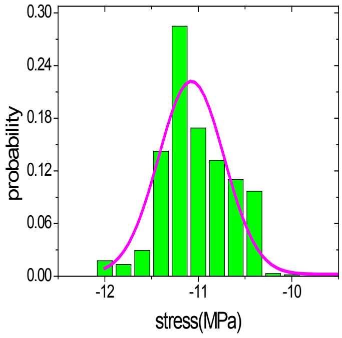

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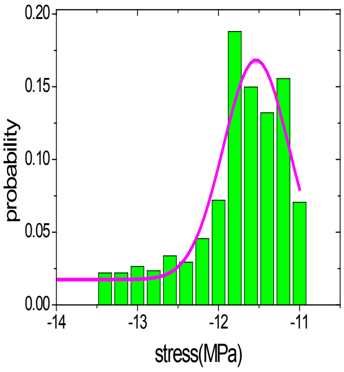

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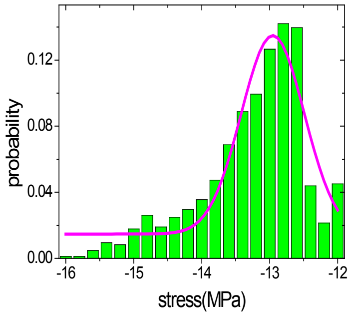
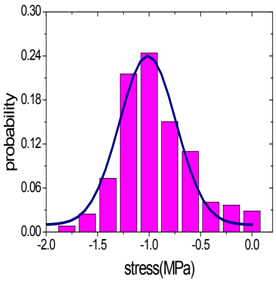
DOI: https://doi.org/10.30564/jaeser.v3i1.1779



(19#)20050704 ～ 20050920

Figure 8. Stress distribution statistics and Gaussian distribution fitting of the data collected from the sensor 4G1h-1



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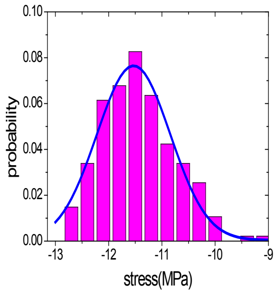

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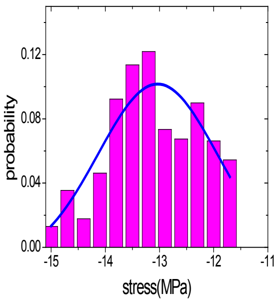

(19#)20050704 ～ 20050920

Figure 9. Stress distribution statistics and Gaussian distribution fitting of the data collected from the sensor 4-5MID-2

It can be seen from Figure 8 and Figure 9 that the stress variation range produced by the live load during the bridge construction phase is about 3MPa, and the load effects distribution basically obey normal distribution. So, we can use the method in Section 3 for the calculation of reliability. At the same time, as the resistance is time-varying, this article only takes mean value of resistance parameters of each construction stage for the calculation of reliability.

Table 4. The standard deviation of the measured load effects probability distribution in each time section

Construction sequence	number of the sensor			
	4G1h-1		4-5MID-2	
	mean(MPa)	Standard deviation(MPa)	mean(MPa)	Standard deviation(MPa)
0#	-1.282	0.533		
1#				
2#	-5.372	1.384		
3#	-7.536	1.082		
4#	-8.047	0.947		
5#	-8.756	0.857		
6#	-9.945	1.335		
7#	-10.496	0.485		
8#	-11.862	0.656		
9#	-11.292	1.630		
10#	-10.634	1.118		
11#	-11.452	0.410		
12#	-11.174	0.501		
13#	-11.023	0.647		
14#	-10.613	0.833		
15#	-10.474	0.778		
16#	-9.734	0.516		
17#	-11.075	0.701	-1.013	0.549
18#	-11.537	0.806	-11.532	1.379
19#	-12.955	0.929	-13.034	2.1098

As the applied stresses and the concrete material strength are basically independent and the stress data is basically obey normal distribution, so, we use Eq. (3) to calculate the reliability values by the monitored data. According Figure 8 and Figure 9, we find that the load distribution function $f_{si}(s)$ is close to the tensile strength distribution function $f_{Rti}(r)$. Therefore, for the data collected from the sensors 4G1h-1and 4-5MID-2, we use $f_{Rti}(r)$ to compute the value β_{ti}. Reference to the method in Section 3, we can get the punctiform time-dependent reliability around the sensor embedded position, which is illustrated in Figure 10.

DOI: https://doi.org/10.30564/jaeser.v3i1.1779

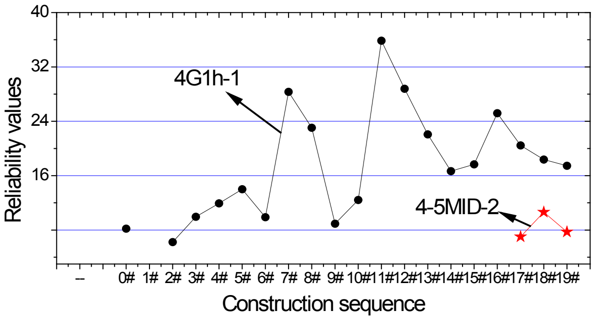

Figure 10. The reliability β_{ti} of each construction stage changes over time which is calculated by $f_{Rti}(r)$

Seeing in Figure 10, the reliability increases gradually made by the subsequent construction stage, and the reliability of the top plate near the bridge cantilever root is more than 16, which is in line with the relevant design requirements. However, the reliability of the bridge mid-span base plate is about 8, which means that the reliability value is relatively low.

5. The Optimal Internal Force Security Level of the Bridge Closure Construction

Generally, the modern large-span continuous rigid frame bridge construction is under monitoring, and so the failure probability of the components or the cross-section in each construction stage can be obtained by the above method. Frangopol [16] puts forward 5 kinds of bridge reliability status, and assumes that the bridge life could be seen as a reliable state process from the intact ($\beta \geq 9.0$) to the unacceptable ($\beta < 4.6$). According to the research suggested by Frangopol, a key scientific problem is how to make the reliability index of the bridge critical section reaches to or more than 9 when the bridge construction is finished.

According to the data form Table 4, the standard deviation of the bridge load effects distribution takes the value 1.35 in this paper when the bridge closure construction is finished. Therefore, in order to make the reliability index $\beta_{ti} \geq 9$, based on the method proposed on the above and according to Eq. (3), that is $|\mu_{si}-\mu_{ti}|>13.8MPa$, scilicet $|\mu_{si}|>16.8MPa$, of which the meaning is that the concrete pressure safety reserve mean at the bottom plate in the bridge mid-span should be at least maintained at above 16.8 MPa (Deduct the prestressed steel strand loss, creep and shrinkage of concrete, and other factors leading to concrete compressive stress loss).

6. Conclusions

In order to ensure the alignment and the internal force of the built bridge meet the design requirements, considering many random factors existing in the construction of the bridge, based on the monitored strain data from the bridge monitoring system, a safety assessment method is suggested for cantilever construction stage stress state of the bridge. The main conclusions are:

(1) The monitored data show that the load effects of this type bridge during construction basically obey Gauss distribution, and so we can use Eq. (2) for reliability calculation.

(2) The concrete optimal pressure safety reserve mean at the bottom plate in the mid-span of this type bridge should be at least maintained at above 16.8 MPa.

However, some important parameter values adopted in this paper are theoretically estimated and should be revised by field test data. The method is simple and practical, and very convenient for engineering applications, which can provide guidance for internal force control of the same type bridges in construction. So, the research results have important significance for improving the construction safety and science of the long-span continuous rigid frame bridges.

Acknowledgements

This study gets supports from Guangdong Province fund project. During the research, Dr Cai and He provide help for the article. So, the first author is very grateful for this.

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