Bridge Structure and Material Stability Analysis Using Monte Carlo and COMSOL 3D modeling

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Abstract. The reinforced concrete structure has the advantages of strong stability, small shrinkage and creep, but there are still some hidden structural dangers in reality. This study introduces the background of stability analysis, takes a truss bridge as an example, uses Monte Carlo simulation and COMSOL Multiphysics software to analyze structural stability, and finds out the relevant factors affecting the stability of the truss. Through calculations and comparison of hundred thousand simulations, the stability of the bridge is one of the most critical elements of a bridge and meets the criteria for bridge performance. In particular, the strength and elasticity of the concrete and steel reinforcement at high temperatures were analyzed. Results show that aggregate type, mixing ratio, curing conditions, heating parameters, and cooling state all contribute subtly to the properties of concrete. High temperature causes the concrete and steel strength decreasing, but normal living temperatures do not pose any threat to bridge structures. For elongation, the effect of temperature on the reinforcement is not obvioust.

Keywords: Comsol model design; Monte Carlo simulation; Concrete Stability; Steel Stability.

1. Introduction

The steel-concrete composite truss bridge has the characteristics of strong dead weight, fast construction and little influence by shrinkage and creep, so it has been developed rapidly. With the continuous increase of truss bridge span and the increase of bridge structure form and material use, the overall or local stiffness decline of the structure appears, which leads to the structural instability of steel-concrete composite beam truss Bridge. For example, the local instability deformation between the web and bottom plate of the composite beam in bending moment area affects the whole beam. Therefore, the local instability phenomenon of steel-concrete composite beam bridge needs more attention.

Through relevant research and comparison, it can be seen that simplifying the bridge analysis will cause many problems. In condition assessment, particularly in the condition assessment of long-span Bridges, there is no perfect theory that can accurately take into account those uncertain factors [1]. This paper uses the Monte Carlo to analyze the stability of the overall structure of the bridge under typical working conditions, and find out the relevant factors affecting the stability of the truss bridge.

2. Background of bridge stability

The instability can be roughly divided into three categories: (1) the instability of some components; (2) partial or total structural instability; (3) locally unstable elements; Among them, local instability is the most serious type, which leads to the most terrible consequences.

After summarizing the failure consequences of these bridges, it can be found that the failure consequences are generally divided into two categories: branch point instability and extreme point instability. The first kind of unbalance is caused by balancing the stability of the branch, and the balance before the buckling structure form is not unified. Once the new equilibrium, the difference between old and new balance could lead to the internal force change of the structure and the model, which is a germplasm change.

The second kind of stability imbalances are often accompanied by structural deformation, and does not belong to the range of elasticity. This means that these imbalances tend to cause more damage to the bridge. In the process of concrete stress, the structure of the stress state and usually assumed one has a big difference. Stress condition is not an ideal state, and the same component of the pure elastic modulus is not changed.

The above two types of buckling problems often appear together, and it is hard to define the general structure of the instability as a first-class or second-class. And in reality, there are more uncertain factors, such as the rod must also have some defects, is not a completely ideal rod, rod material parts may be uneven, axial load eccentric loading and so on. These factors may lead to structural instability [2].

3. Calculation principle of the Monte Carlo

The main method to analyze bridge structure stability used in this paper is the Monte Carlo. The essence of Monte Carlo method is a numerical method to solve problems using probability theory through a large number of random trials, and the basic idea is based on the similarity between probability and volume. Monte Carlo method is a mathematical or physical model based on the principle of sampling statistics to solve practical problems [3]. Usually, the first step is to put forward a probability model with some connection with the actual problem, and prepare enough input variable values from enough experiments. Because there are similarities between the model and the actual problem, these generated can simulate the real problem in the change of the random factors. Finally, the computed eigenvalues of this model (i.e., values of output variables or standard deviations) can provide an approximate solution to a real problem.

The likelihood of fulfilling a predetermined function within a given timeframe and under a given condition is referred to as structural reliability. Let X = (X1, X2... Xn) X might be the geometric size of the structure, the physical and mechanical characteristics of the material, the action of the structure, the resistance of the mechanism, etc. T is the set of N random variables that determine how well the structure works. The following is the structure's function, or failure function.

$$Z = G(x) = G(X1, X2, ..., Xn) \tag{1}$$

It is predetermined that $Z > 0$ denotes a dependable state for the structure and a failure state for the structure. By considering the effect of different random elements on structure functions, structural reliability analysis may be used to calculate the failure probability Pf of a structure or a structure component.

The probability distribution of load, load effect, resistance and other parameters in bridge structure has been given in "Uniform Standard for Reliability Design of Highway Engineering Structure", which can be modified according to the actual situation of the project. The steps for reliability analysis of bridges by the Monte Carlo method are as follows:

(1) Write the functional functions of each cross-section of bridges Z = G (X) = G (X1, X2... , Xn);

(2) Determine the probability distribution of each random variable in the functional function according to the bridge specification and actual measurement;

(3) According to the probability distribution of each random variable, a certain sampling method is adopted to generate the random number of each variable, and each sampling can generate a group of (Xi1, Xi2... , Xin) T;

(4) Calculate the specific value of function Zi at the ith sampling according to step (1), and a total of N groups are generated.

(5) Count the occurrence times of function $Zi < 0$, and finally get the failure probability of each section of the bridge Pf = Nf /N.

4. Bridge Structure Stability Analyze

When analyzing the structure, the prerequisites include whether the effects of wind load are considered, whether the occurrence of earthquakes is considered, and many other natural hazards that can occur. However, this paper does not consider the effects of any external forces, but only considers how to determine if there is any risk of collapse when designing a bridge.

In this part, three of the most commonly used methods of structural analysis are introduced. The first is to compare the capacity and sum of the load (live load, dead load, and additional load) of the bridge design. The second is to use Monte Carlo Simulation in Matlab and sampling analysis to get the probability of collapse of the bridge, which is Pr in Matlab. The third is 3D modeling using COMSOL to analyze and compare each component of the bridge through 3D force diagrams. Each method is mutually reinforcing.

4.1. Comparison of the loads capacity and sums

If the value of capacity is not indicated in the design, the following equation could be used.

$$P = (ULrP + A\sigma R0)/2 \tag{2}$$

The result could be compared with the sum of the load. By the definition of capacity, it is suggested to keep the difference of capacity and sum of loads as always greater than 0, rather than equal or less than 0. As engineers, they might hope the difference can be maximized because its increase indicates the whole bridge structure is more stable. But in real life, engineers need to control the budget if the budget permits. It is the simplest and most straightforward way. Without considering external forces and natural disasters, this method only requires a comparison of two data to get a Ture or False answer. It is very suitable for the first structural stability analysis when the engineer designs the bridge, so that even if there are some design loopholes, they can be corrected immediately.

4.2. The probability of collapse of the bridge by Monte Carlo Simulation

Before a bridge is already completed and in operation, comparing two data is not sufficient. Once the bridge collapses, the consequences would certainly be very serious, so the Monte Carlo method could be used for simulation. It's a multiple probability simulation used to estimate an uncertain event's possible outcomes.

The advantage of the Monte Carlo method is that a large number of simulations can be performed by computer, and it is a good way to check whether the bridge is at risk of collapse after comparing the capacity and sum of loads.

But assuming that the failure probability is not 0 in a hundred thousand times simulation, Matlab cannot find which part is most likely to cause the collapse.

4.3. 3D modeling using COMSOL

COMSOL Multiphysics software is one of the best tools to solve this problem. First is to input the live load of the bridge itself, the dead load, and then whether additional load is a car or a train. For convenience, we can set it as a rectangle moving at constant speed on the bridge, and input the length and the load it generates. With these data, COMSOL can output a 3D force diagram of the bridge structure. Here is the sample results of the output (Figure 1).

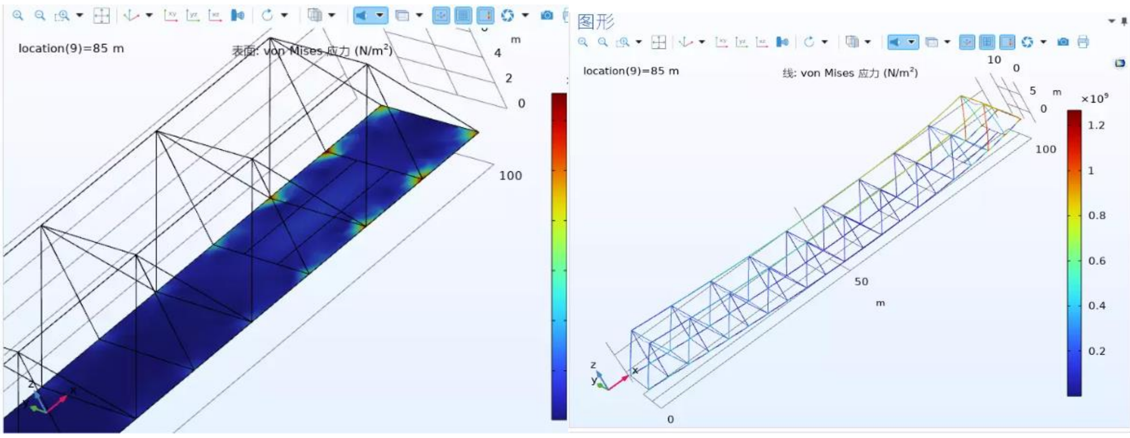

Fig. 1 Sample results of the 3D force diagram output of the bridge structure

Next, these two pictures are used to understand how to analyze properly. On the far right side of the diagram, from red to blue, the forces received by the bridge structure change from large to small. In the first diagram, when the train/car passes through this part of the bridge, the force on the connection between the beam and the main body of the bridge is much larger than that on the main body. The color of the force on these pivot points from the outermost green yellow until the intersection point out of the red, indicating that the force on these parts closer to the intersection point is greater. The second diagram shows that the beams are under much greater force than the bridge body. If this bridge is still in the design stage, then the force capacity of the joints and beams shoud be strengthened. Otherwise, if this bridge has already been built and operated, according to the Comsol diagrams, after 40 or 50 years(normal bridge life), the maintenance team should prioritize these frew parts. This method is interconnected with the two previous methods. Although Comsol can be a little more difficult to manipulate than Matlab, analyzing which parts are more likely to be vulnerable after sampling to obtain the probability of collapse is a very critical part of the bridge structure analysis process.

5. Steel and concrete stability analysis

Truss bridge encounters many special features in the construction process, such as long construction period, environmental change, climate change, etc. With subjective factors, such as the load capacity of the bridge structure, we also need some objective factors to calculate the probability of structural stability of a real-life bridge. Many objective factors can lead to structural instability, such as poor material quality, substandard concrete, poor quality steel, overweight trains, natural disasters, temperature, time-induced material loss, etc.

This paper mainly focused on the material issues of the bridge. The bridge we chose is mainly composed of steel and concrete materials. These two materials are not only the main materials of our bridge but also the main components of most bridges in real life. For example, this paper compares many types of concrete and steel on the market and argued that even the most common engineering materials would ensure that our structure would not fail. Unless this paper encounters a very poor quality material, such as concrete, that is as unstable as plastic; therefore, we need to analyze the material's properties to do so.

The first and biggest problem is the temperature. At different temperatures, the structure between the atoms inside the material changes slightly; like water, when the temperature is very low, the structural stability between the water atoms is more stable than when the temperature is high. There is no doubt about this when the water temperature reaches 100 degrees Celsius, the water turns into water vapor. This problem also occurs in two materials, steel, and concrete. So it needs to study whether the change in temperature affects the stability of these two materials, which could lead to the structural stability of the truss bridge. For the temperature issue, it is hard to do own experiments to conclude that such materials can be tested. Professional instruments are needed to perform multiple tests at temperatures up to 1000 degrees Celsius or even higher. So it needs to use the data from the literature combined with the real situation to reach a conclusion.

5.1. The impact of temperature on concrete and steel strength

According to a study of concrete at high temperatures in China, the experimentalists used tests with concrete made of different kinds of concrete. Concrete is an artificial stone produced by mixing cement, coarse aggregate (crushed stone or pebbles), fine aggregate (sand), admixtures, and water, which is hardened, so the compressive properties of different types of concrete are different. Aggregate type, mixing ratio, curing conditions, heating parameters, and cooling state all contribute subtly to the properties of concrete [6,7].

Figure 1 deals with the strength of different types of concrete at high temperatures. It shows that all concrete start to drop significantly only after the temperature reaches 200 degrees, a temperature that is not possible in real life or, perhaps more precisely, around our bridges. When considering the temperature, we also need to consider the environment around the bridge. If it is a flammable area like a forest, the bridge must remain stable in case of fire.

The changes in steel reinforcement at high temperatures are also needed to consider. Rebar is an artificial alloy of various metals [4]. Unlike concrete, the strength of steel does not change significantly when the temperature is up to 500 degrees and does not begin to slowly decay with time until above 500 degrees (Figure 2). Therefore, in general, normal living temperatures do not pose any threat to bridge structures.

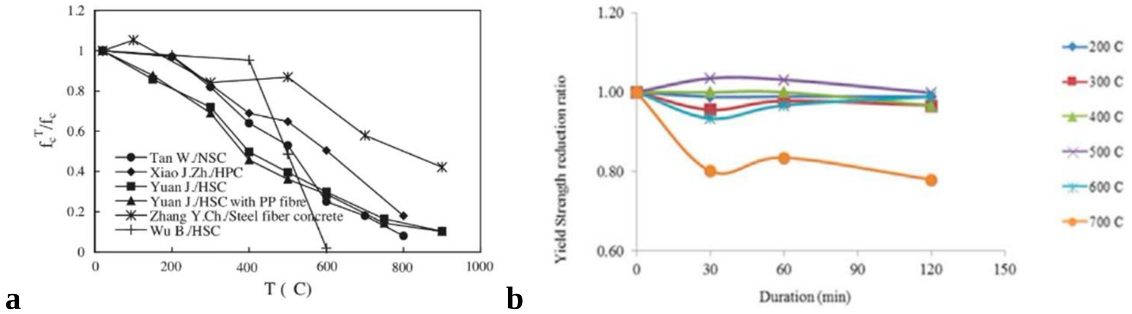

Fig. 2 The strength of (a) different types of concrete [5] and (b) steel with temperatures [4]

5.2. The impact of temperature on concrete and steel elasticity

After considering the influence of temperature on the strength of the material, the influence of temperature on the material's elasticity is also required. Proper elasticity is an important condition to ensure the stability of the bridge. When the temperature rises or under different pressures, the bridge bends slightly, this bending is not visible to the naked eye, but the bridge's structure is needed to withstand these bends. And the material's elastic properties are to bend to prepare. In the design of concrete structures, the modulus of elasticity is quite important and needs to be defined. Elemental linear analysis based on the theory of elasticity is sometimes used to meet the requirements of limit and serviceability limit states [8].

For the consideration of elasticity, two points are considered. Firstly, the tensile strength is how much this material can be stretched at high-temperature definite conditions. If the material is stretched a lot, it also means that the material is very soft. For the bridge, when a material is soft, it could lead to structural instability because it changes the bearing capacity of the bridge. The next thing to consider is elongation, which means that if the elongation of the material is a lot, it could also have an impact on the stability of the whole bridge, even leading to collapse.

Through the concrete investigation, the tensile strength of concrete is very low, especially in high-temperature conditions. When the temperature is above 400 degrees, the tensile strength decreases significantly. Although the tensile strength also decreases before 400 degrees, it is not significant compared to our normal living temperatures. But then, it is important to consider whether factors such as fire could cause structural damage to our bridge structures due to changes in the tensile strength of the concrete at high temperatures. Likewise, the modulus of elasticity, which decreases as the temperature increases, affects the material's stability only at extremely high temperatures. Figure 3 shows that the tensile strength of the heap decreases with time, and the tensile strength decreases rapidly when the temperature reaches 700 degrees [9]. For elongation, the effect of temperature on the reinforcement is not obvious. However, considering actual building situation, such temperatures do not occur either, but other forces need to be considered to cause the elongation of the material (Figure 3).

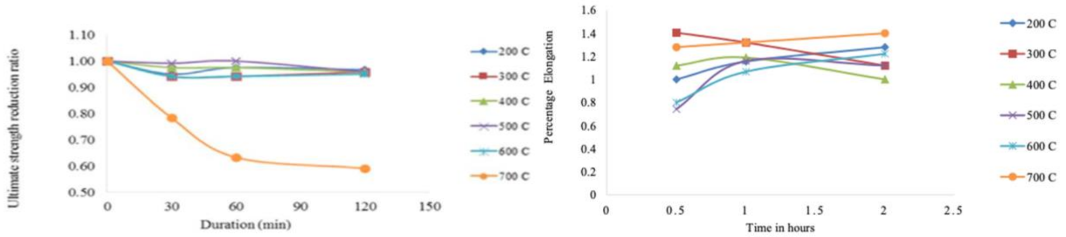

Fig. 3 (a) The tensile strength and (b) elongation of the heap with time [10]

6. Conclusion

This paper calculates the possibility of failure of a bridge through several factors.

The first is the various aspects of the bridge force analysis. By drawing and calculating the force analysis, we can learn whether the bridge itself is a stable structure. After knowing the stability of the bridge structure, the second through the bridge loads and additional loads to calculate the bridge in normal use cannot maintain stability, but also to know the maximum can withstand the loads. The stability of the bridge is one of the most critical elements of a bridge, so all three analysis methods are indispensable, the quantity of Monte Carlo simulation must be large and the probability obtained must be infinitely close to 0 or equal to 0 (depending on the number of simulations). Ahrough the three-dimensional force analysis, the maintenance team can more precisely prioritize and focus the inspection sequence.

To rigorously ensure the stability of the bridge, this paper also to analyzes the various characteristics of the materials used in the bridge. The effect of temperature on the material is a threat to the stability of the bridge. In general, for concrete, temperature does not have a significant effect on the properties of this material. At high temperatures, the strength of concrete decreases, but only to a small extent, so there is no significant change in the strength and elasticity of the material. For steel, however, temperature can have a significant effect at high temperatures, especially for elasticity. The elasticity of steel decreases sharply at temperatures above 400 degrees. But from the temperature conditions of daily life, these changes in material properties will not affect the stability of the object of investigation, that is, the bridge.

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