Application Research on Magnetic Coupling Stress Testing Technique for In-service Steel Bridge

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Abstract. Magnetic effect of ferromagnetic materials was discussed, the magneto-mechanical properties of ferromagnetic materials were studied, as well, Jiles Atherton constitutive mode was studied. Through the establishment of concrete filled steel tubular arch bridge structure calculation model, analysis the boom in tension and compression of the magnetic coupling. Results show that the resultant magnetic coupling model of Q345 steel derrick, the boom and load changes, the change of the magnetic parameters is more sensitive, can be better applied to the stress testing of such components.

1. Introduction
In recent years, with the development of transportation, the steel structure bridge has been widely used. But due to the stress of the steel bridge structure are complicated, it is difficult for designers to accurately estimate the actual internal force values of each link and node. Therefore, in order to detect stress of the steel bridge structure, and, in order to assess the reliability of steel bridge in service, the changes rules between the design internal force and the actual value have been studied, nondestructive stress testing for steel bridge structure is one of the hot issues, stress detection based on magnetic coupling effect got the attention of the scholars both at home and abroad [1-2]. In this paper, take Suspenders of CFST arch bridge as the research object, the principle of magnetic coupling stress testing technology is researched from a new Angle.

2. Magnetic Effect of Ferromagnetic Materials and Magnetic Hysteresis Model

2.1. Magnetic Effect of Ferromagnetic Materials
Magnetic effect refers to the ferromagnetic materials is associated with spontaneous magnetization and technology magnetization between magnetic and mechanical properties of the effect of mutual contact and influence each other.

Magnetic effect mainly includes the following several aspects

(1) the magnetostriction

Magnetostrictive effect is the most common and most widely used magnetic effect [3-4]. Commonly used magnetostrictive effect refers the ferromagnetic materials when subjected to external magnetic field, the tiny changes of the length of the material in magnetic field direction. The rate of
change is called magnetostrictive coefficient of per unit length, for ferromagnetic materials, average between 10^{-6}-10^{-5}.

(2) magnetic volume effect
This effect refers to the outer ferromagnetic materials when the magnetization of the magnetic field, its volume change. Because of this effect first observed in the metal Ni by Barrett, it is also known as Barrett (Barrett) effect. Magnetic volume effect in ferromagnetic materials from paramagnetic state after the Curie temperature into a sequence of magnetic state will have the volume change, this is due to the effect of exchange of the ferromagnetic material in magnetic ordered field caused by the spontaneous magnetization, rather than caused by the technology of magnetization of the magnetic field outside, sometimes it is called exchange magnetostriction. Magnetic inverse effect of volume effect is also called the Nagaoku-Honda effect.

(3) magnetic torsion effect
This effect refers to the proper magnetic circuit is formed on the magnet, when a current through the magnetic body distortion will occur and can be used to make reverse motor, etc. This effect is also known as Wiedenmann effect, and its inverse effect refers to a longitudinal magnetization of ferromagnetic rod exert torque, the causes of longitudinal current change, namely that the circumference of the vertical rod axis direction has a magnetic field and the change of intensity of magnetization, also known as Wertheim effect. This mechanical distortion in the magnetic body, and in the secondary coil current AnTi-Wiedenmann effect, can be used in the production of all kinds of torsion sensor.

(4) magnetic bending effect
This effect is a ferromagnetic material bar bending, and when the vertical (axial) magnetization, the phenomenon of iron bar would be straightened, the magnetic field makes a ferromagnetic material rod bending effect, also known as Guillemin effect, can be used in the production of all kinds of actuators.

(5) magnetic rotation effect
This effect refers to the free hanging in the direction of the axis of the ferromagnet with external magnetic field or the external magnetic field is reversed [5], ferromagnetic experience by torque effect and produce the effect of the rotation, also known as Einstein DE Haas effect. Its inverse effect called Barnett effect, which is when the original not magnetized ferromagnetic turns, will produce certain magnetization. Magnetic rotation effect associated with ferromagnetic micro electronic spin in the body.

(6) magnetic elastic effect
This effect refers to the ferromagnetic material under plus a magnetic field, the modulus of elasticity (young's modulus) will change effect, also known as the $\Delta E$ effect or Brackett effect, can be used for acoustic delay line or sensors [6].

(7) magnetic rigid deformation effect
This effect refers to the ferromagnetic material under plus a magnetic field, its stiffness coefficient will change effect, also known as the Kimball effect, which can be used in the production of sensors or actuators.

2.2. Magnetic Hysteresis Model
Assume that polycrystalline ferromagnetic materials for isotropic materials, under the effect of magnetic field $H$, its typical magnetic domain (with the magnetic moment $m$), per unit volume energy type as follows

$$E = -\mu_0 m \cdot H$$

(1)

In equation (1), $H$ is within the material within the practical domain under magnetic field intensity, not the external magnetic field.
The coupling effect between the introduction of magnetic domain, the energy per unit volume can be expressed as

\[ E = -\mu_0 m \cdot (H + \alpha M) \]  \hspace{1cm} (2)

In equation (2), \( \alpha \) is an average field coupling parameters between adjacent magnetic domain. Set up effective magnetic field \( H_e = H + \alpha M \), the magnetization of the response of the effective field can also be expressed as follows

\[ M = M_s f(H_e) \]  \hspace{1cm} (3)

In equation (3), \( f \) for arbitrary function of effective field; At that time \( H_e = 0, f(0) = 0 \). At that time \( H_e \to \infty, f(\infty) = 1 \). \( M_s \) for saturated magnetization.

Formula (3) and the corresponding to the lowest energy state of the magnetic domain statistical distribution, and does not take into account related to material structure characteristics, such as location and nonmagnetic impurity inclusions, etc. Therefore, using this equation can be obtained without hysteresis magnetization curve or ideal magnetization curve. Under the effect of magnetic field \( H \), the domain walls along the curve to reach real equilibrium position. Therefore, the equation can be written as the type

\[ M_{an}(H_e) = M_s f(H_e) \]  \hspace{1cm} (4)

In equation (4), \( M_{an} \) for no hysteresis magnetization.

For common no hysteresis magnetization, selection function \( f \) for the Langevin function \( L(H_e) \), available

\[ M_{an}(H_e) = M_s (\coth(H_e/a) - (a/H_e)) \]  \hspace{1cm} (5)

In equation (5), \( a \) has the dimension of magnetic field intensity, characterization of no hysteresis shape of the curve, and is proportional to the effective density of the magnetic domain and absolute temperature, can be defined as follows \( a = k_B T / \mu_0 \langle m \rangle \), among them, \( k_B \) for the Boltzmann constant \( (1.38 \times 10^{-23} \text{jk}^{-1}) \), \( T \) is the absolute temperature, \( \mu_0 \) for the vacuum magnetic permeability \( (4\pi \times 10^{-7} \text{H/m}) \), \( \langle m \rangle \) for effective magnetic domain size. Revised Langevin equation does not describe the normal dc magnetization of ferromagnetic well, because the model ignores the magnetization of the irreversible changes, such as when the domain wall movement to pinning point location, the magnetization of the irreversible change.

When the magnetic field does total energy per unit volume is equal to the balance of specimen magnetic energy required to do the work of a magnetic field, the magnetic domain wall will return to its starting position, namely

\[ E = \int H dB = \frac{1}{\mu_0} \int B dB - \int M dB \]  \hspace{1cm} (6)
Among them, the external magnetic field on the right side of the second said on the specimen of the work done.

When there is no pinning point of ferromagnetic domain wall is pressure, moving in the domain wall, magnetization along no hysteresis curve to reach equilibrium. Therefore, the equation can be expressed as follows

\[
\int MdB_e = \int M_{an}(H_e)dB_e
\]  

(7)

In equation (7), \( B_e = \mu_0 H_e \)

It is well known that under the action of outside magnetic field, by pinning point in ferromagnetic materials (such as non magnetic inclusions, voids, non-uniform stress zone), have set back domain wall movement. The existence of these defects will lead to the decrease of the initial magnetic permeability and ferromagnetic materials with the increase of coercive field.

3. Analyses of Numerical

3.1. Model Structure

This project depends on the Lan-cang river bridge construction project, located in the area of Tibet Changdu town, the basic intensity of \( \text{Ⅶ} \) degrees in this region, the ground motion peak acceleration of 0.1 g, the design, the bridge seismic press \( \text{Ⅶ} \) degrees fortification, main bridge upper structure using single span 125 m, half through bridge concrete filled steel tubular arch bridge with 31.25 m rise, arch axis equation of catenary, arch axis coefficient is 1.347, for precast reinforced concrete hollow slab bridge and arch bridge using bored piles foundation. Little pile number approach of upper with 15 m prestressed reinforced concrete hollow slab, approach of using in the pile size 1-15 m prestressed concrete hollow slab and 1-15 m sector plate.

In five main arch rib section of production, arch rib dimensions are subject to loft to arch rib arch axis, namely for the arch rib axis length \( L \), arch rib steel pipes of longitudinal seam, the butt weld require the use of automatic welding, full penetration, groove form is determined by the welding way; All welds are \( \text{Ⅰ} \) weld.

The arch bridge of the arch rib in the 2.7 m high, arch rib on the bottom chord pole diameter of 950 mm, adopt 20 mm thick steel plate. Bridge upper structure of concrete filled steel tube adopts C30 concrete and prestressed concrete beams and surfacing layer USES the C40 concrete, adopting C35 concrete bridge panel.

3.2. Establish the Model Structure

The calculation model was established based on general finite element calculation program structure, respectively, set up concrete filled steel tube concrete material for ordinary concrete and different replacement rate of recycled concrete structure calculation model. The calculation model of the arch structure as shown in figure 1.

![Model structure](image)

Figure 1. Model structure.

A single arch rib is divided into 24 section, section forms of dumbbell arch section, the end section of the arch foot \( \text{Ⅰ} \) combination section, the section form and cross section geometric parameters as
shown in figure 2(a), in addition to the arch foot end section, the rest of arch ring cross section II combined section, the section form and the cross section of geometrical parameters as shown in figure 2(b).

![Figure 2. Dumbbell arch cross section.](image)

In order to simplify the calculation, the mechanics model is set up, according to the area and the principle of changeless of section steel content and the section of equivalent to the above two kinds of ideal round steel tube concrete section, simplified section geometric parameters and steel content are shown in table 1.

| cross section features | combination section I | combination section II |
|------------------------|-----------------------|-----------------------|
| containing steel ratio (%) | 9.2                   | 8.1                   |
| cross section diameter D (mm) | 400                   | 380                   |
| thickness of the steel tube t (mm) | 2.80                  | 2.76                  |

### 3.3. Technical Solution

This paper intends to combine the theoretical analysis and computer simulation analysis method, the deformation and stress of ferromagnetic materials can be expressed as the constitutive relationship between magnetic field.

\[
\epsilon_{ij} = \epsilon_{ij}(\sigma_{ij}, H_i) \\
B_i = B_i(\sigma_{ij}, H_i)
\]

(8)

In equation (8), \(\sigma_{ij}\) as the stress, \(\epsilon_{ij}\) strain, \(B_i\) as the magnetic induction intensity, \(H_i\) magnetic field intensity. It can be seen that when the independent variable is stress and magnetic field intensity, the output is the strain and magnetic induction intensity, so it gets in the experiment are must measure the amount of basic, test is difficult. In the applied load and magnetic field, under the condition of measuring the specimen deformation and magnetic induction intensity, reflected by magnetic force characteristic curve of ferromagnetic materials, such as magnetic hysteresis and magnetostriction curves and magnetic induction intensity – stress curves, etc., at the same time be able to reflect the
magnetomechanical properties of ferromagnetic materials important parameters, lay the foundation for the theoretical research and engineering application.

3.4. The Calculation Results

Based on the vault boom, for example, set in the calculation of derrick for Q345 steel, the vault derrick and magnetic loading at the same time, the magnetic field is obtained by numerical simulation calculation parameters and the corresponding relation of derrick stress. Under the action of tensile stress in the derrick model of magnetization curve of the specimens is shown in figure 3. Can be seen from the diagram, when the magnetic field intensity, namely when the magnetization process of transition from the second to the third phase, the stress sensitivity of magnetization gradually, and with the increase of tensile stress, the magnetization and increasing, related close to the linear change.

![Figure 3](image3.png)

**Figure 3.** The magnetization curve for specimens under the action of tensile stress.

When to compressive stress, compressive stress test magnetization curve of the specimens under the action of the derrick model as shown in figure 4. Can be seen from the diagram, when the magnetic field intensity, namely when the magnetization process of transition from the second to the third phase, the stress sensitivity of magnetization gradually, and with the increasing of compressive stress and the intensity of magnetization is constantly decreases, and still close to the linear relationship between related changes.

![Figure 4](image4.png)

**Figure 4.** the magnetization curve for specimens under the action of compressive.
Conclusions
Various magnetic effect of ferromagnetic materials is discussed in this paper, study the magnetomechanical properties of ferromagnetic materials, studies the Jiles Atherton constitutive model. Through the establishment of concrete filled steel tubular arch bridge structure calculation model, analysis the boom in tension and compression of the magnetic coupling. Results show that the resultant magnetic coupling model of Q345 steel derrick, the boom and load changes, the change of the magnetic parameters is more sensitive, can be better applied to the stress testing of such components.

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