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Simulation analysis of prestressed tensioning whole process on direct constraint method

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The accuracy simulation of the prestressed tensioning effect is the foundation of prestressed bridge design, construction and reinforcement. Direct constraint method was used in the application of prestressed tensioning whole process simulation analysis on the background of prestressed testing experiment. Its aim was to achieve the real simulation of interaction between prestressed tendon and concrete in the tensioning whole process. Three-dimensional solid elements were adopted to simulate pre-stressed reinforcement unit and concrete unit. Bilinear Coulomb friction was adopted as the friction form between prestressed tendon and concrete. Direct constraint method that has the characteristics of good stability and fast convergence speed was used to calculate the effective stress of prestressed tendon at each tension stage. The loss of one-way stress was also calculated. The effective prestressed values by simulation on direct constraints method can be well with the measured values and the theoretical values on Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts. The method has theoretical basis on accurately simulating the actual stress in different stages of the prestressed tendon. It can be helpful for bridge design and reinforcement.

Keywords-Direct constraint method; Finite element simulation; Tensioning whole process; Effective prestress; Prestressed tendon

Методом прямого ограничения проведено моделирование процесса предварительного натяжения на основании экспериментов по тестированию предварительного напряженных систем. В качестве модельного объекта рассмотрено взаимодействие между предварительно напряженой арматурой и бетоном. Для имитации армирующих блоков и блоков бетона был адаптирован трехмерный метод упругого твердого тела. В качестве модели, описывающей силы трения, возникающие между предварительно напряженной арматурой и бетоном, рассматривается модель кулоновского трения. Для вычисления эффективных напряжений армирующей матрицы на разных этапах натяжения был использован метод прямого ограничения, обладающий хорошей стабильностью и высокой скоростью сходимости. Показано, что значения эффективных преднапряжений, полученные путем моделирования методом прямого ограничения, находятся в качественном согласии с экспериментальными и теоретическими значениями.

Моделювання натягу в попередньо напружених системах. *Каймінь Лю.*

Методом прямого обмеження проведено моделювання процесу попереднього натягнення на підставі експериментів по тестуванню попередньо напружених систем. В якості модельного об'єкту розглянуто взаємодію між переднапруженою арматурою і бетоном. Для імітації блоків, що армують та блоків бетону був адаптований тривимірний метод пружного твердого тіла. В якості моделі, яка описує сили тертя, що виникають між попередньо напруженою арматурою і бетоном, розглядається модель кулоновського тертя. Для обчислення ефективних напружень матриці, що армує, на різних етапах натягу був використаний метод прямого обмеження, що володіє гарною стабільністю та високою швидкістю збіжності. Показано, що значення ефективних переднапружень отриманих шляхом моделювання методом прямого обмеження, знаходяться в якісній згоді з експериментальними та теоретичними значеннями.

1. Introduction

Accurate simulation of prestressed tension effects is the basis for the rational design of prestressed concrete bridge. Old bridge reinforcement, fill-tensioned of prestress or supplement of external prestress and other special circumstances require more detailed and effective structural tension simulation. But the accurate numerical analysis is very difficult. It is often used as a boundary or an initial condition applied to the calculation model, such as the common methods of the equivalent load method, the cooling method and the initial strain method [1-4]. Because of the common node or coupling between prestressed tendon unit and concrete unit, the above methods cannot simulate the interaction between prestressed tendon and concrete. It also cannot accurately analyze the stress development of tendon in tension and loading stages.

The application of contact friction analysis is the basis for the more accurate analysis. However, the problems of convergence and numerical stability on the friction model need to be solved. The finite element analysis software MSC.MARC is one of the common analysis programs in nonlinear problems. It provides a variety of contact friction models. But it has not been applied for engineering analysis on tensioning prestressed tendon with high stress and large displacement. In this paper, based on the application of MSC.MARC analysis software and the 3-D solid element simulation of prestressed reinforcement unit and concrete unit, the friction model was established. The simulation analysis of slip contact in the whole tension stage was carried out by two engineering projects.

2. Coulomb bilinear models on contact analysis

Prestressed tendon unit and concrete unit adopted the solid unit. They were defined as the deformable contact by CONTACT and specified for TOUCHING contact form by CONTACT TABLE in MSC.MARC software. The friction form between concrete and prestressed tendon was defined as Coulomb bilinear friction. Coulomb bilinear friction model assumes that viscous friction and sliding friction are respectively corresponding to the reversible (elastic) and irreversible (plastic) relative displacement. It uses a sliding surface representation φ, as shown in Figure. 1 [5-6].

$$\phi = \left\| f_t \right\| - \mu f_n \qquad (1)$$

Where: f_t means shear stress. f_n means normal reaction force. μ means the friction coefficient of prestressed tendon and pipeline wall. The viscous limit distance δ adopts the default value in the model, which is 0.0025 times of the average unit scale of deformable contact bodies.

$\Delta u_t < \delta, \phi < 0$, Viscous friction

$\Delta u_t > \delta, \phi > 0$, Sliding friction

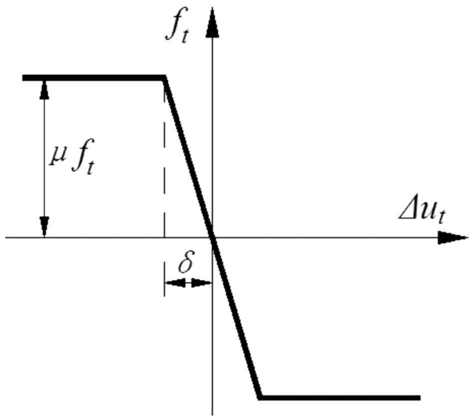

Fig. 1. Bilinear friction model

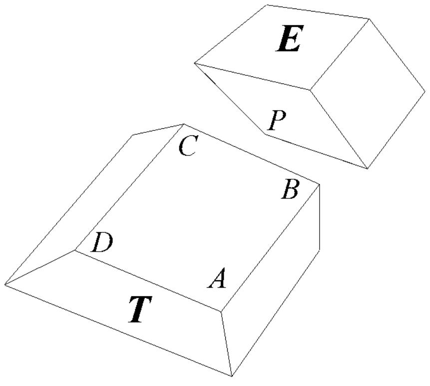

Fig. 2. Contact constraint

Contact analysis function in MSC.MARC provides a contact algorithm on direct control, as shown in Fig. 2.

Node P of contact unit E is in contact with the surface of the target unit T. When the both are in contact, the degree of freedom of point P in the A-B-C-D surface direction can be eliminated. It only has tangential motion along the A-B-C-D surface. By the method of eliminating point P freedom, two units are made together, as shown in Formula 2 [7-8].

$$\begin{bmatrix} \left[{}^{t}K^{E}\right] & 0 \\ 0 & \left[{}^{t}K^{T}\right] \end{bmatrix} \begin{Bmatrix} u^{E} \\ u^{T} \end{Bmatrix} = \begin{Bmatrix} f^{E} \\ f^{T} \end{Bmatrix} \qquad (2)$$

Where: u is the displacement increment and f is the residual force vector.

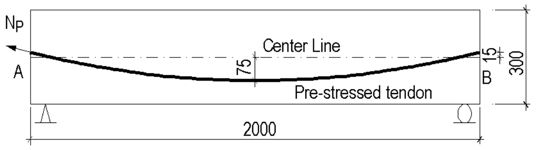

Fig. 3. Prestressed tendon layout of rectangular section beam (mm)

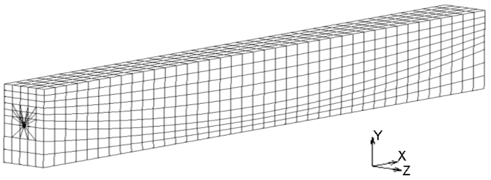

Figure 4. Finite element model of prestressed beam with rectangular section

3. Finite element model

A. Prestressed simply supported beam with rectangular section

Geometric parameters of prestressed simply supported beam with rectangular section are shown in Fig. 3.

Concrete strength is C50, and the elastic modulus is 34.5GPa. Prestressed tendon chooses the low relaxation steel strand with the elastic modulus of 196.0GPa. The cross section size is 30mm × 30mm, and consistent with the dimension of the cross section of the original model. Friction coefficient μ between prestressed tendon and pipeline wall is 0.25. Friction influence coefficient κ of local deviation of per meter pipe is 0.0015. Prestressed tendon adopts the parabolic curve style. The parabolic equation can be expressed as Equation 3.

$$y = f \cdot \left(\frac{2x}{l}\right)^2 - e_1 \tag{3}$$

Where: f is strand vector high. e_1 is the vertical distance from the axis to the end of strand.

Unit models of prestressed tendon and concrete was respectively established. Prestressed elements were embedded into the concrete element and made the nodes on the fixed end of prestressed tendon and the near concrete nodes coupling, as the anchor end. A rigid surface on tension side at the tendon end was created and bonded with prestressed tendon. It was controlled by one node that will transfer the tension force to prestressed tendon. Force was exerted on the concrete of tension end and the value was the same with that of control node, but the direction was opposite. While concrete nodes subjected the reaction was coupled to prevent stress concentration. Prestressed tendon and concrete was defined as two groups with different deformation body. The friction coefficient between them was defined as 0.25 in Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridge and Culverts (JTG D62-2004) [9]. Friction type was Coulomb bilinear friction. The finite element model is shown in Fig. 4.

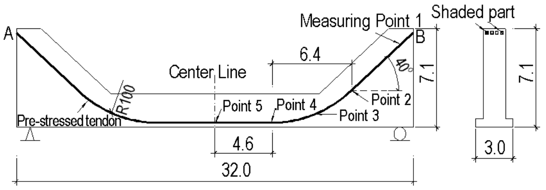

Fig. 5. Prestressed tendon layout of beam with T-shaped section (mm)

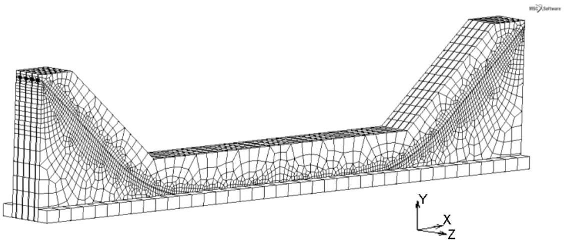

Fig. 6. Finite element model of prestressed eam with T-shaped section

B. Prestressed simply supported beam with T shaped section

Material properties of prestressed simply supported beam with T shaped section are same as that of beam with rectangular section. Equivalent cross section size of prestressed tendon is 40mm × 42mm. It consists of three straight line segments and two arc segments. The actual measuring point arrangement is shown in Fig. 5. Each prestressed beams arranged five measurement points. The effective one-way stress of shaded part in two prestressed beam were tested. Two prestressed beam are respectively embedded corrugated metal pipe and corrugated plastic pipe. Mold resistance coefficient of corrugated metal pipe and corrugated plastic pipe is measured.
Corrugated metal pipe: μ=0.24 κ=0.0020
Corrugated plastic pipe: μ=0.16 κ=0.0014 [10]

The finite element model is shown in Fig.6.

4. Analysis of the results

A. Prestressed simply supported beam with rectangular section

Tensile force of prestressed tendon in the model was 1200kN. Tension simulation process was divided into 100 load steps. Tensile force of each load step was 12kN and the total time was 1s.

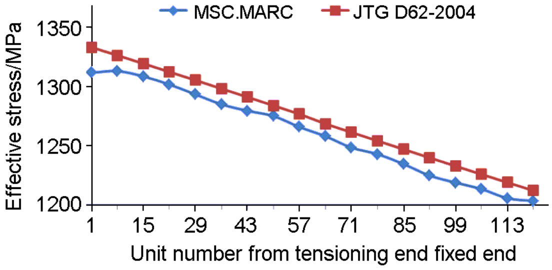

Fig. 7. Effective stress of prestressed tendon

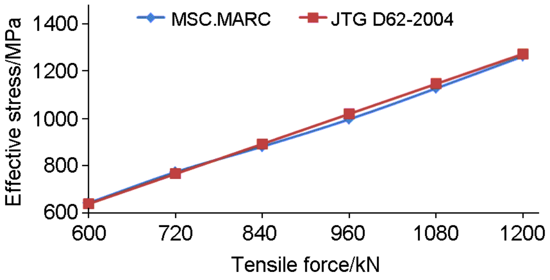

Fig. 8. Effective stress of mid-span unit

When the tensile force reached 1200kN, the effective frictional stress by MSC.MARC simulation and JTG D62-2004 is shown in Fig. 7.

When prestressed tendon was stretched by one-end, it can be seen from Fig. 7 that the effective tensile stress by MSC.MARC simulation and JTG D62-2004 was similar. But the simulation tension value is smaller than that of JTG D62-2004.

Prestress loss value of mid-span unit changed with the load in Fig. 8.

It can be seen from Fig. 8 that effective stress of mid-span unit by MSC.MARC simulation and JTG D62-2004 was similar. When the load reached 960kN, the simulated values and theoretical values are 995.23MPa and 1018.05MPa respectively. At this point, the both maximum deviation was 2.24%. When the tension stage was completed, the largest elongation of prestressed tendon was 13.02mm.

B. Prestressed simply supported beam with T shaped section

Tensile force of prestressed tendon in the model was 2287 kN. Prestressed tendon was stretched by two-end. Tension simulation process was divided into 100 load steps. Tensile force of each load step was 22.87kN and the total time was 1s.

1) Metal bellow

Effective stress of Prestressed tendon of metal bellow by MSC.MARC simulation, JTG D62-2004 and field measurement are shown in Figure 9.

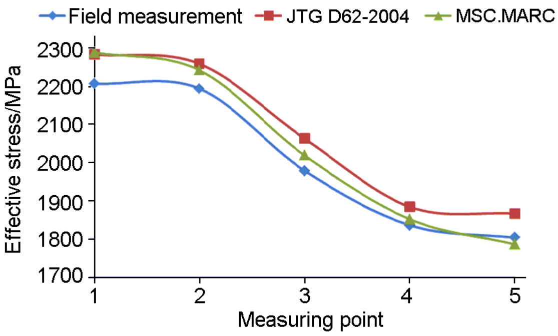

Fig. 9. Effective stress of tendon of metal bellow

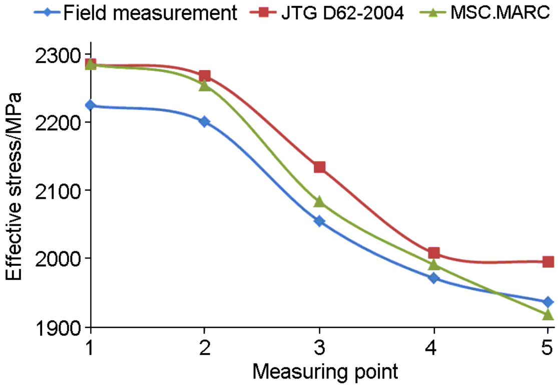

Figure 10. Effective stress of tendon of plastic corrugated pipe

It can be seen from Figure 9. that the effective stress of metal bellows decreases gradually. Three curves of MSC.MARC simulation, JTG D62-2004 and field measurement are similar basically.

The deviation of measured prestressed values and JTG D62-2004 calculated prestressed values on No. 3 measuring point were the maximum, 4.26%. The deviation of No. 2 measuring point was the minimum, 2.62%.

The deviation of measured prestressed values and MSC.MARC simulated values on No. 1 measuring point were the maximum, 3.71%. The deviation of No. 4 measuring point was the minimum, 0.12%. When the tension stage was completed, the largest elongation of prestressed tendon was 127mm.

2) Plastic corrugated pipe

Effective stress of tendon of plastic corrugated pipe by MSC.MARC simulation, JTG D62-2004 and field measurement are shown in Fig. 10.

It can be seen from Figure 10 that the effective frictional stress of plastic corrugated pipe decreases gradually. Three curves of MSC. MARC simulation, JTG D62-2004 and field measurement are similar basically.

The deviation of measured prestressed values and JTG D62-2004 calculated values on No. 3 measuring point was the maximum, 3.85%. The deviation of No. 4 measuring point was the minimum, 1.86%.

The deviation of measured prestressed values and MSC.MARC simulated values on No. 1 measuring point was the maximum, 2.72%. The deviation of No. 5 measuring point was the minimum, 0.98%. When the tension stage was completed, the largest elongation of prestressed tendon was 151mm.

According to the above analysis, it can be seen that the effective stress deviation of MSC. MARC simulation, JTG D62-2004 and field measurement is in 5%, which meets the engineering accuracy requirement. However, the drawback of this approach only considers the effective stress from friction. It does not consider the impact of per meter local variations of channel on friction. In addition, using solid element to simulate the prestressed tendon may enlarge bending stiffness. But the both impacts on the results are tiny, and need further study in future.

5. Conclusions

In this paper, bilinear friction model of prestressed tendon and concrete is established by using the MSC.MARC software. It can analyze the true stress of prestressed tendon in tension and loading stage. Tension simulation results show that the values of MSC.MARC simulation, JTG D62-2004 and field measurement are similar basically. The method is reasonable with analysis of convergence speed and good stability algorithm. It provides an effective method of analysis for the bridge structural design, reinforcement and other engineering. For prestressed concrete bridge, combined analysis of prestressed tendon and concrete is still in the exploratory stage. Simplified methods widely used become slightly rough in old bridge reinforcement analysis and other conditions, because they need more precise conclusion.

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