Development of Strength Calculation Program for Arbitrary Section Based on BIM Technology

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Abstract: BIM technology is rapidly and profoundly affecting all fields of bridge construction. How to apply BIM technology to reinforcement calculation of arbitrary components is a problem worthy of study. Based on Dassault Systems 3DEXPERIENCE R2018X, this paper successfully solves the problem of strength calculation of arbitrary section of reinforced concrete members by means of analytic method, iterative method and graphical method, applying the principle of material mechanics, and compiles the program of strength calculation of arbitrary section of allowable stress method under Dassault 3DE platform.

1. Introduction

Bridge is an important part of traffic construction. With the development of the times and the improvement of people's aesthetic level, bridge design tends to be practical and beautiful. BIM technology with its characteristics is rapidly and far-reaching impact on the development of bridge construction, has gradually become an important means of information technology to improve the level of bridge technology and management efficiency [1]. With the requirement of bridge landscape, the shape of reinforced concrete members is becoming more and more complex. How to apply BIM technology to the calculation of biaxial large eccentric compression of any section of reinforced concrete members is a problem worth studying.

The calculation problem of reinforced concrete members subjected to biaxial large eccentric compression is complex, which is not discussed in general books on design principles of reinforced concrete structures, and few domestic scholars have done research in this field. Among them, Yu Qi [2] studied the reinforcement calculation of rectangular section. Starting from the mechanical properties of the rectangular section with tangent angle, the main centroid is sought by using the theorem of translation axis and rotation axis, and then the zero stress line equation and stress function are limited in the original centroid coordinate system by coordinate transformation, and the final zero stress line is solved by iterative method, and the maximum compressive stress of concrete and the maximum tensile stress of reinforcement are obtained; Tong Senlin [3] studied the reinforcement calculation of round-end section, regarded the effective area as a combination of several simple figures, and then used translation axis, rotation axis and coordinate transformation to iteratively solve the final zero stress line, thus solving the maximum compressive stress of concrete and the maximum tensile stress of reinforcement, and giving the calculation diagram of stress redistribution coefficient of round-end section. Yang Yongyi [4] studied the calculation of non-uniform reinforcement with arbitrary section,
and developed a calculation program based on AutoCAD.

Dassault Systemes 3DE platform is an open, interconnected, data-driven, model-based and virtual-real integration business platform. Based on the principle of making full use of the existing BIM model and the principle of material mechanics, the author successfully solved the strength calculation problem of arbitrary section of reinforced concrete by using the BIM technology and using the analytical method, iterative method and graphic method, and worked out the Arbitric Fabrication Program for Allowable Stress (AFPA) under the platform of Dassault 3DE.

2. Calculation procedure and principle

2.1 Three coordinates of the cross section

In order to calculate the zero stress line of the section, three coordinate systems are established here: a. Structural coordinate system \((x - y)\); b. Equated section coordinate system \((x' - y')\); c. Equated section principal centroid coordinates system \((x'' - y'')\).

![Diagrammatic drawing of bidirectional loading on section](image)

Figure 1 Diagrammatic drawing of bidirectional loading on section

2.2 Equation calculation of initial zero stress line

For bidirectional large eccentric compression cross section, the initial zero stress line equation in the structural coordinate system can be expressed as

\[ y = k_0 \cdot x + p_0 \]  \hspace{1cm} (1)

Where

\[ k_0 = -\frac{M_y \cdot I_x}{M_x \cdot I_y}, \quad p_0 = -\frac{N \cdot I_y}{F \cdot M_x} \]

\(F, I_x, I_y\) is the converted sectional area composed of the bar ring and the full section of concrete and its moment of inertia on the axis and \(y\) axis, i.e

\[ F = n \cdot F_g + F_h, \quad I_x = n \cdot I_{gx} + I_{hx}, \quad I_y = n \cdot I_{gy} + I_{hy} \]  \hspace{1cm} (2)

\(g, h\) Represents the bar ring, concrete respectively.

Similarly, for the unidirectional large eccentric compression section, its initial zero stress line equation can be expressed as

\[ y = p_0 \quad \text{and} \quad x = -\frac{p_0}{k_0} \]
2.3 Calculation of zero stress line equation of new section

The new section refers to the transformed section after deducting the concrete tensile zone. The previous zero stress line (or initial zero stress line) is an edge of the new section. After calculating the new section, a new zero stress line will be generated, and the new line will be more inclined to the compression zone than the old zero stress line.

2.3.1 Geometric properties of effective transformed section in transformed section centroid coordinate system

Let the centroid of the concrete section after deducting the concrete tensile zone be \( \bar{x}_h, \bar{y}_h \), the geometric characteristics relative to the centroid position are \( F_h', I_{hx}', I_{hy}', I_{kxy}' \).

Let the centroid of the non-uniformly arranged bar strip be \( \bar{x}_g, \bar{y}_g \), the geometric property of the centroid position relative to itself are \( F_g', I_{ghx}', I_{gy}', I_{gxy}' \).

Then the centroid of the effective area coordinate is \( \bar{x}, \bar{y} \)

\[
\begin{align*}
\bar{x} &= (F_h' \cdot \bar{x}_h + n \cdot F_g' \cdot \bar{x}_g) / F_s' \\
\bar{y} &= (F_h' \cdot \bar{y}_h + n \cdot F_g' \cdot \bar{y}_g) / F_t' \\
F_s' &= F_h' + n \cdot F_g'
\end{align*}
\]

(3)

(4)

where \( F_s' \) is transformed area of effective cross section.

By applying the translation axis theorem, the translation geometric properties of the effective translation section can be obtained as

\[
\begin{align*}
I_{x'} &= I_{hx'} + F_h' \cdot (\bar{y}_h - \bar{y})^2 + n \cdot F_g' \cdot (\bar{y}_g - \bar{y})^2 \\
I_{y'} &= I_{hy'} + F_h' \cdot (\bar{x}_h - \bar{x})^2 + n \cdot F_g' \cdot (\bar{x}_g - \bar{x})^2 \\
I_{xy'} &= I_{kxy'} + F_h' \cdot (\bar{y}_h - \bar{y})(\bar{x}_h - \bar{x}) + n \cdot I_{gxy'} + n \cdot F_g' \cdot (\bar{y}_g - \bar{y})(\bar{x}_g - \bar{x})
\end{align*}
\]

(5)

2.3.2 Geometric properties of effectively translation cross sections in principal centroid coordinates \([3,5,6]\)

By using the definition of rotation axis, the rotation angle \( \theta_p \) of principal centroid of effective area can be obtained

\[
\theta_p = \frac{1}{2} \arctan \left( \frac{2 I_{xy'} v}{I_{y'} - I_{x'}} \right)
\]

(6)

The principal moment of inertia is:

\[
\begin{align*}
I_{x'} &= u + v \cos 2\theta_p - I_{xy'} \sin 2\theta_p \\
I_{y'} &= u - v \cos 2\theta_p + I_{xy'} \sin 2\theta_p
\end{align*}
\]

(7)

where

\[
\begin{align*}
u &= \frac{I_x - I_y'}{2} \\
v &= \frac{I_x + I_y'}{2}
\end{align*}
\]

(8)

The eccentric moment and bending moment in the \( x'' - y'' \) coordinate system are
2.3.3 New zero stress line equation

The stress function in the \( x^*' - y^*' \) coordinate system can be expressed as

\[
\sigma_h = \frac{N}{F_s^*} + \frac{M_x^*}{I_x^*} x^*' + \frac{M_y^*}{I_y^*} y^*' \tag{11}
\]

Applying the coordinate system transformation and the variable substitution principle, we can obtain

\[
\sigma_h = B' \cdot y + C' \cdot x + A' \quad \tag{12}
\]

where \( A = \frac{N}{F_s^*} \), \( B = \frac{M_x^*}{I_x^*} \), \( C = \frac{M_y^*}{I_y^*} \),

\[
B' = B \cdot \cos \theta_p + C \cdot \sin \theta_p \quad \quad C' = C \cdot \cos \theta_p - B \cdot \sin \theta_p \quad \quad A' = A - (B' \cdot \overline{y} + C' \cdot \overline{x})
\]

Then the zero stress equation of the new section can be expressed as

\[
y = k \cdot x + p \quad \quad \tag{13}
\]

where \( k = \frac{C'}{B'} \), \( p = -\frac{A'}{B'} \).

2.3.4 Iteration and stress calculation

The maximum tensile stress of the new section of concrete occurs at any point along the previous zero stress line \( (y = k_0 \cdot x + p_0) \).

If \( |k - k_0| < \varepsilon \), and \( |p - p_0| < \varepsilon \)

Then the result converges calculation of \( \varepsilon = 1 \times 10^{-6} \)

Or else, Let \( k_0 = k \), \( p_0 = p \), then doing iterative computations

Suppose that the points at which the compressive stress of concrete and the tensile stress of reinforcement will be calculated are \((x_h, y_h)\) and \((x_g, y_g)\) respectively

Then the compressive stress of concrete and the tensile stress of reinforcement are

\[
\sigma_h = B' \cdot y_h + C' \cdot x_h + A' \quad \quad \tag{14}
\]

\[
\sigma_g = n \cdot (B' \cdot y_g + C' \cdot x_g + A') \quad \quad \tag{15}
\]

3. Secondary Development Based on Dassault 3DE Platform

3.1 Development of CGM Model Operation\(^8\)

Because of the complexity of section shape and reinforcement arrangement, in order to reduce manual input, the section strength calculation program makes full use of parametric BIM model, and all the
geometric parameters needed for calculation are obtained from BIM model. Users only need to select geometric entities, intersecting planes and cross-sectional shafting, and other geometric parameters involved in strength calculation are obtained from geometric Boolean and geometric topological operation results of the three. The program involves the secondary development of mathematical operation, geometric operation, topological operation and feature operation of CGM model on 3DE platform. Different operations have different use scope, time, resources and required element levels. They are sorted from the perspective of memory and time: feature operation > topological operation > geometric operation > mathematical operation.

![3DE Geometric Modeler Architecture](image)

**Figure 2** The 3DE Geometric Modeler Architecture

The program converts discrete point steel bars into continuous steel bars for calculation. Because the calculation of cross-section strength involves geometric iterative operation, in order to improve the operation speed and reduce memory consumption, the program uses a large number of geometric and topological operations and mathematical functions to improve the operation efficiency. The main frameworks involved include Mathematics, GMModelInterfaces and GMoperatorsInterfaces.

### 3.2 Interface and Component Development

Software Component Architecture (SCI) is the next generation logical model of software engineering following process model and object-oriented model. Object-oriented technology can only realize limited reuse by reusing existing classes in class library, while software component mechanism provides the highest level of code reuse. Software component architecture has three basic concepts: framework, component and object bus. Dassault 3DE platform adopts a variety of software technologies supporting component technology, and all internal modules are implemented by CNEXT.

From the business point of view, the author compiles the cross-section strength calculation interface, and encapsulates the program as a component (AFPAImpl). The client can use the executable code through the exposed interface, which not only hides the implementation details, but also ensures the upward compatibility of the client application using it.

### 3.3 Interaction Development

There are three main commands in 3DE: single-step command, dialog command and status command. (1) Basic commands, also known as (Basic Commands): The runtime user cannot have additional options and cannot stop from its start to its end, also known as single-step commands, which are derived from the CATCommand class. (2) Dialog Box Commands: The user can enter parameter values or select options. The dialog box itself is a command, not a part of other commands. This kind of command is derived from the CATDlgDialog class. (3) State Commands: State commands are
simulated as state machines, and high-level dialog commands can be formed through the combination of state, migration (or transition). A command can have several states, each of which lets the user select an object, enter a parameter, or select an option. According to the selected object, input parameters or options, whether the conditions are met or not is judged. If the corresponding conditions are met, the migration is triggered, and the next state is jumped to execute until the end of the command. Dialog box can be used for status dialog command as parameter or option input interface. This class of commands is derived from the CATStateCommand class.

The program adopts state command and filters and selects input objects in turn through state transition; In order to display Chinese conveniently, the dialog box is defined in AFPAPanel class by code.

![Figure 3 Command and Dialog Box Derivation, Aggregation Diagram](image1)

![Figure 4 Command state transition diagram](image2)

### 3.4 Program Introduction

Based on Dassault Systems 3DEXPERIENCE R2018X and Visual Studio 2015, a program for calculating the strength of arbitrary section by allowable stress method is developed. This program is closely combined with the current railway code, and can be used to calculate the reinforced concrete reinforcement and concrete stress redistribution of any biaxial compression-bending member. The program has friendly interface and good error correction ability, and can give corresponding hints to some misoperation of users.

![Figure. 5 AFPA section strength calculation dialog box](image3)
4. examples

4.1 Calculation and analysis of biaxial stress of circular end hollow section (reinforced concrete)
This example is taken from reference [5], the specific calculation parameters are shown in Table 1, and the calculation results are shown in Table 2. From Table 2, it can be seen that the calculation results of AFPA are in good agreement with those of reference [5].

The parameters in Table 1 are the length of straight line section, the outer radius of arc section, the inner radius of arc section, the radius of steel bar in arc section and the width of unit length of steel bar.

| Project | $b$ | $R_0$ | $R_e$ | $R_g$ | $t$ | $N$ | $M_x$ | $M_y$ |
|---------|-----|-------|-------|-------|-----|-----|-------|-------|
| Unit    | M   | M     | M     | M     | 0.001 | 8000 | 6000   | 9000   |
| Numerical value | 2.1 | 1.15  | 1.0   | 1.1   | 0.001 | 8000 | 6000   | 9000   |

Note: The elastic modulus ratio is 10

| Project | $\sigma_{h,max} (MPa)$ | $\sigma_{g,min} (MPa)$ |
|---------|------------------------|------------------------|
| Reference [3] | 15.056 | -105.199 |
| AFPA    | 15.0562 | -105.1985 |
| Error%  | 0          | 0          |

4.2 Calculation and Analysis of Stress Redistribution of Round End Solid Section [5] (Concrete)
This example is taken from reference [5], the specific calculation parameters are shown in Table 3, and the calculation results are shown in Table 4. From Table 4, it can be seen that the calculation results of AFPA are in good agreement with those of reference [5].

The parameters in Table 3 are the length of straight line segment and the radius of circular arc segment respectively.

| Project | $b$ | $R$ | $N$ | $M_x$ | $M_y$ |
|---------|-----|-----|-----|-------|-------|
| Unit    | M   | M   | KN  | KN*m  | KN*m  |
| Numerical value | 2.1 | 1.15 | 5301 | 1960   | 3714   |

Note: The elastic modulus ratio is 10

| Project | $\sigma_{h,max} (MPa)$ |
|---------|------------------------|
| Ref. [5] | 1.805                  |
| AFPA    | 1.805                  |
| Error%  | 0                      |

5. Conclusion
(1) It is feasible to apply BIM technology to the strength calculation of arbitrary section;
(2) The calculation program based on BIM technology can make full use of BIM model and reduce the amount of user data input;
(3) Encapsulating the section strength calculation program as a 3DE platform component is more convenient for the expansion and maintenance of the platform;
(4) In the next step, the cross-section strength calculation component is combined with the extended feature technology of 3DE platform to realize the model-based correlation design.
Foundation items
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