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Establishment and Validation of Finite Element Model for Reinforced Concrete Columns

Yulin Li*
School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454003, China
*278312350@qq.com

Abstract

Reinforced concrete structures are widely used in buildings in China. However, research on the mechanical properties of reinforced concrete components remains limited due to experimental constraints and economic factors. This study establishes a mesoscale numerical model of reinforced concrete (RC) columns using Python and ABAQUS software, followed by comparative analysis with experimental results. The results indicate that the predicted load-displacement curves and ultimate bearing capacities align closely with experimental data, demonstrating high consistency between the model and real-world conditions. This work lays a foundation for further research on the mechanical behavior of RC columns.

Keywords

Reinforced Concrete; Mechanical Properties; Mesoscale; Numerical Model.

1. Introduction

As a core load-bearing form in modern civil engineering, the accurate prediction of the mechanical performance of reinforced concrete structures has long been a focus in academia and engineering. Reinforced concrete (RC) columns, serving as typical axial compression and bending members, play a critical role in transferring loads in buildings, bridges, and underground structures. Traditional macroscopic finite element models, based on continuum assumptions and homogenization methods, are widely applied in engineering design but fail to reveal mesoscale damage mechanisms such as concrete cracking, steel-concrete interface slippage, and failure at the aggregate-paste interfacial transition zone (ITZ).Under extreme loads (e.g., earthquakes, explosions, or long-term corrosion), macroscopic models often exhibit significant deviations from experimental results in predicting nonlinear responses, damage evolution, and failure modes. These limitations hinder the precise evaluation of structural performance under complex conditions and impede the innovative design of high-durability and high-toughness concrete materials.

However, there are many factors affecting the compressive performance of reinforced concrete members, and the failure phenomena are complex and diverse. However, due to the limitations of experimental conditions and economic factors, the research on the mechanical properties of reinforced concrete members is still limited. In particular, reinforced concrete columns are widely used, but how to break through the limitations of test conditions and further study the mechanical properties of reinforced concrete columns is still an urgent problem to be solved. The finite element simulation technology can fill this gap. It can not only deeply analyze the mechanical behavior of reinforced concrete columns without the limitation of experimental conditions, but also effectively predict their mechanical properties, which provides a theoretical basis for design optimization and structural improvement.

At present, many studies have regarded concrete as a macroscopic homogeneous material, but it cannot reflect the internal cracking, damage and failure mechanism of concrete materials

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under external loads. Therefore, the mechanical properties of concrete at meso-scale have high research value. At the mesoscopic level, concrete can be regarded as a multiphase composite material composed of coarse and fine aggregate, mortar matrix and transition zone interface (ITZ), micro cracks or pores. Micromechanical methods are generally divided into two categories [1] : micromechanical finite element method and theoretical analysis method. The finite element method of micromechanics is to calculate the macro stress-strain relationship by dividing the structure into grids. Firstly, the stress-strain field is obtained, and then the macroscopic stress-strain relationship is obtained by homogenization method. According to the microscopic field, the damage failure process and plastic yield of composite materials are further studied [2]. The theoretical analysis method is to equivalent the inhomogeneous medium to the ideal homogeneous medium, which has the macroscopic equivalent physical properties of the inhomogeneous medium. The theoretical analysis method is used to study the elastic properties of composite materials in the elastic range, and now it is also used to predict the inelastic properties. Studying the macroscopic mechanical properties of concrete from a mesoscopic perspective has become a hot topic in the research field of concrete materials and components [3] [4] [5].Ma et al. [6] studied the dynamic damage and failure mechanism of concrete under static preload, and proposed a mesoscopic dynamic model. Studies have shown that static preload has an enhancement effect on dynamic tensile strength. This effect is essentially caused by the two-sided nature of concrete strain rate strengthening and damage degradation. Sun et al. [7] established a multi-phase mesoscopic model of concrete considering the change of interfacial transition zone thickness with aggregate size, and realized the parallel simulation of concrete damage and crack propagation under high cycle fatigue load. The analysis results show that the fatigue cracks in concrete mainly occur near the ITZ and gradually enter the cement mortar matrix to form finite-size cracks. These cracks interact with each other until the dominant crack appears and expands endlessly, resulting in the failure of the specimen. Peng et al. [8] studied the fracture process and failure mechanism of concrete under uniaxial compression load, and adopted a new finite element method-basic force element method in numerical simulation modeling. It is found that the aggregate distribution only affects the crack location and failure path, but does not affect the macroscopic elastic modulus and strength of concrete materials. The uniaxial compressive strength of concrete specimens increases significantly with the increase of coarse aggregate content.Song and Jun [9] carried out the research on the creep mechanism of concrete at meso-scale, and proposed the meshing method of aggregate and mortar at meso-scale by using Monte Carlo method. At the same time, the composite material model of aggregate, cement mortar and water content at meso-scale was established by combining mixing theory and porous medium theory. The research shows that the model can effectively simulate the creep motion law inside concrete. Chen Xiangyu [10] established the lattice model of concrete specimens by using MATLAB language, and carried out numerical simulation on the basis of this model. The research shows that under the condition of similar boundary conditions, specimen size, aggregate volume fraction and aggregate gradation, the change of aggregate distribution in concrete specimen will not significantly change the mechanical properties of concrete specimen, but will have a certain impact on the crack propagation of the specimen.

In this paper, starting from the mesoscopic research scale, combined with the theory of mesoscopic mechanics, the mesoscopic numerical model of RC column is established by using Python language to redevelop ABAQUS finite element software. On the basis of verifying the feasibility of the model, it provides a reference for the subsequent exploration of the mechanical properties of RC structure.

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2. Finite Element Model Establishment and Verification

In this chapter, Python language is used to program a program that can quickly and efficiently establish the meso-components of concrete (including aggregate, cement mortar and interfacial transition zone), and ABAQUS finite element software is used to establish the meso-numerical model of RC column. The compressive performance of the model is numerically simulated, and the simulation results are compared with the experimental results. At the meso-scale, concrete materials are often regarded as heterogeneous three-phase composites composed of aggregate particles, cement mortar matrix and interfacial transition zone between them. The aggregate is assumed to be polyhedral aggregate, and the secondary concrete is used. The volume fraction of aggregate is about 30 %. According to the Walraven formula [11], based on the random distribution characteristics of concrete aggregate, the random aggregate generation program is written, and the 3D mesoscopic model of plain concrete column is established. On this basis, the steel bar is inserted to establish the three-dimensional mesoscopic model of reinforced concrete column.

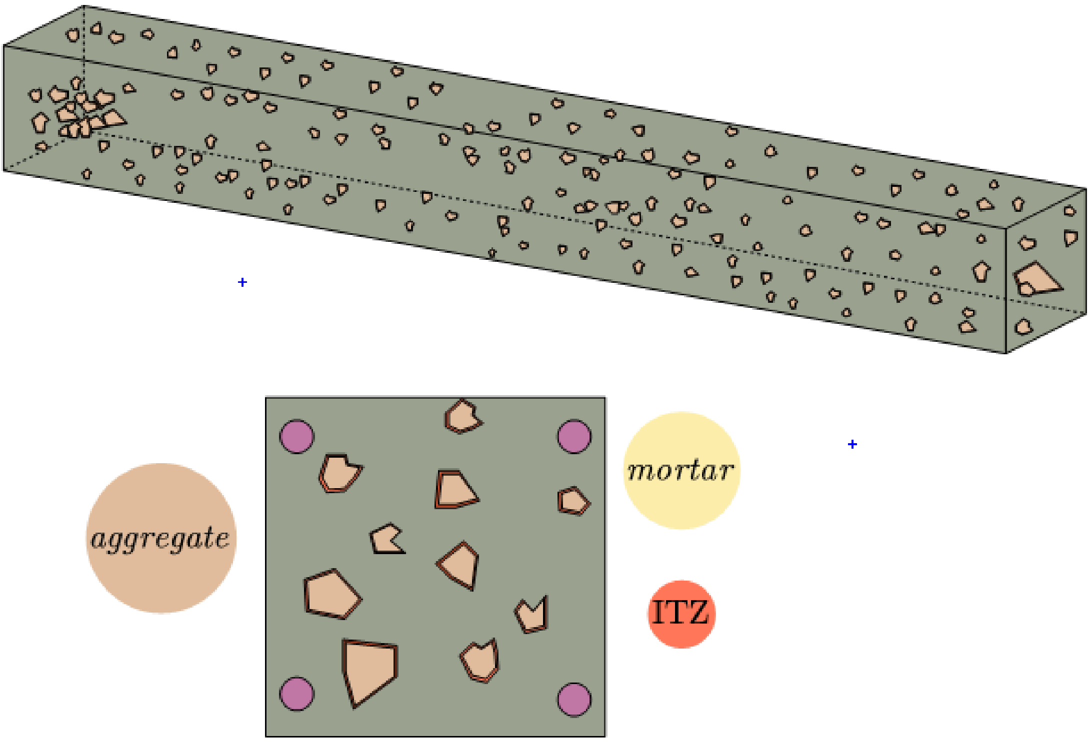

Fig 1. Mesoscopic finite element model of RC column

2.1. Aggregate Generation and Delivery Method

2.1.1. Polyhedral Aggregate Generation

In a 3D polar coordinate system, spherical aggregates were approximated using 26 nodes and 48 triangular elements. Random perturbations in radius (r), azimuth (θ), and polar (φ) angles generated irregular polyhedral shapes. Optimal parameters (radius fluctuation: 0.2–0.4; angular fluctuation: 18°–36°) were determined through comparative analysis with real aggregates.

When each aggregate vertex fluctuates randomly relative to its initial position, the generation of concave and convex aggregates can be realized. It is assumed that the initial parameters of point n are r_{n0}, θ_{n0}n0 and φ_{n0}, and the aggregate control particle size D is determined by the aggregate gradation. The fluctuation range of aggregate particle size r is between ($-D/2$,$D/2$);the fluctuation range of d_θ and d_φ is between(-22.5°,22.5°). Therefore, the aggregate vertex function is expressed as follows :

$$\begin{cases} r_n = r_{n0} + d_r \cdot \text{random}(\text{-}1,1), d_r \in \left(-D/2, D/2\right) \\ \theta_n = \theta_{n0} + d_\theta \cdot \text{random}(\text{-}1,1), d_\theta \in \left(-22.5°, 22.5°\right) \\ \varphi_n = \varphi_{n0} + d_\varphi \cdot \text{random}(\text{-}1,1), d_\varphi \in \left(-22.5°, 22.5°\right) \end{cases} \tag{1}$$

In the formula, random ( ) is a random function, which means that a random number is generated between (– 1,1). The vertex connection is realized by calling WirePoly-Line ( ). The necessary parameters of this method are the coordinates of the two endpoints, which can be obtained by the vertex data in the index database. In order to avoid redundant line segments, the order of connection between vertices follows the following principles. First, connect horizontal edges, such as P2 to P3, P3 to P4, etc. ; then connect the vertical edge, such as P2 to P10, P10 to P18, etc. ; finally, the oblique edges are connected, such as P9 to P10, P2 to P11, and so on, as shown in Figure 2. After the connection of 26 vertices is completed, the surface is divided into 48 regions by each edge. Then call the method Cover-Edges ( ) to close each side as a triangular plane ; when the outer surface is completely generated, the method AddCells ( ) is called to transform the shell composed of the outer surface into a solid, that is, a single random concave-convex polyhedron aggregate is obtained.

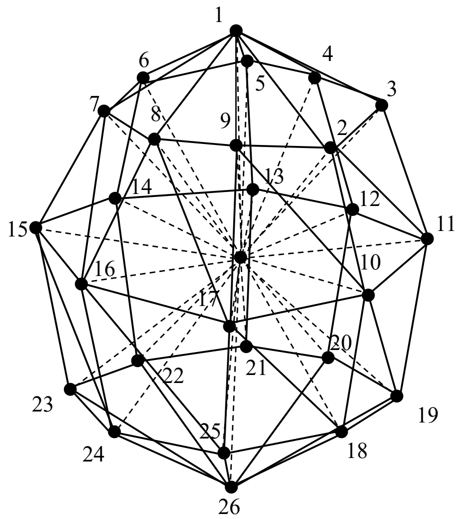

Fig 2. Polyhedron space framework

By randomly fluctuating the aggregate vertices in the three dimensions of r, θ, and φ according to Formula (1), a random concave-convex aggregate is manufactured. The more significant the vertex fluctuation is, the more irregular the aggregate shape is. After a large number of trial calculations and comparisons with the shape of the actual aggregate, it is found that when the fluctuation range of the particle size is set between 0.2 and 0.4, and the angle fluctuation range is controlled between 18° and 36°, a three-dimensional random concave-convex aggregate that is consistent with the actual aggregate shape can be obtained. Fig.3 shows several typical polyhedral aggregates with different shapes generated under different angle fluctuation ranges.

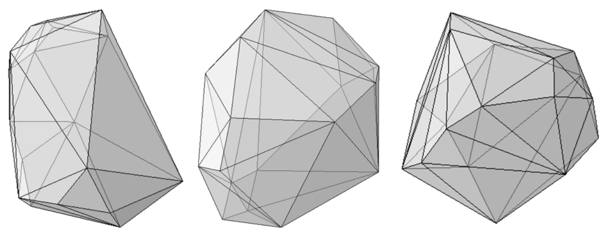

Fig 3. Polyhedral aggregate at random angle

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2.1.2. Aggregate Gradation

On the basis of a large number of experiments, American scholar Fuller (FullerWB) and others put forward the maximum density curve of concrete aggregate. Fuller 's ideal gradation curve is the maximum density curve formed by the proportion and content of aggregate particle size. The corresponding parabolic equation is as follows:

$$P(D<D_0)=100\sqrt{\left(\frac{D_0}{D_{\max}}\right)} \tag{2}$$

In the formula : P is the mass percentage of aggregate particle size less thanD_0 ; D is the particle size of aggregate ; $D_{\max}$ is the maximum aggregate size.

2.1.3. Polyhedral Aggregate Delivery

After generating a single concave-convex aggregate, the aggregate library can be constructed according to the specific grading requirements of the project. In practical engineering applications, aggregates are usually classified into two types : continuous grade and single grain grade, and single grain grade is generally divided into four grades. According to the specific requirements of the project, the mixing of concrete will refer to the specific aggregate gradation ratio, and the relevant aggregate size distribution of graded concrete is described in table 1.

Table 1. Different gradation aggregate particle size distribution table

	aggregate particle size			
	5~20	20~40	40~80	80~150
aggregate category	small	Medium	Large	Extra-large
grading of aggregates	1:0:0:0	5.5:4.5:0:0	3:3:4:0	2:2:3:3

The delivery process of the aggregate is shown in Figure 4.

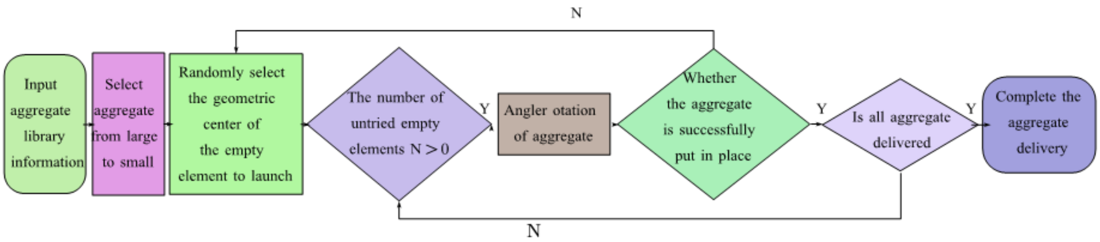

Fig 4. Polyhedral aggregate delivery process

2.2. Constitutive Relationship of Materials

2.2.1. Constitutive Relationship of Concrete

The concrete material can be regarded as a three-phase heterogeneous composite material composed of aggregate, mortar matrix and interfacial transition zone (ITZ) at the meso-scale. The aggregate strength is much higher than the tensile strength of mortar matrix and ITZ [27], so it is assumed that the aggregate particles are linear elastic materials. The concrete damage plasticity (CDP) model in ABAQUS was used to describe the mechanical behavior of mortar and bonding interface.

2.2.2. Constitutive Relationship of Steel

The stress-strain relationship of steel adopts ideal elastic-plastic model and double broken line model. The expression is shown in Equation (3) :

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$$\sigma = \begin{cases} E_S\varepsilon & (\varepsilon \leq \varepsilon_y) \\ f_{sy} & (\varepsilon > \varepsilon_y) \end{cases} \tag{3}$$

In the formula:

- steel stress;

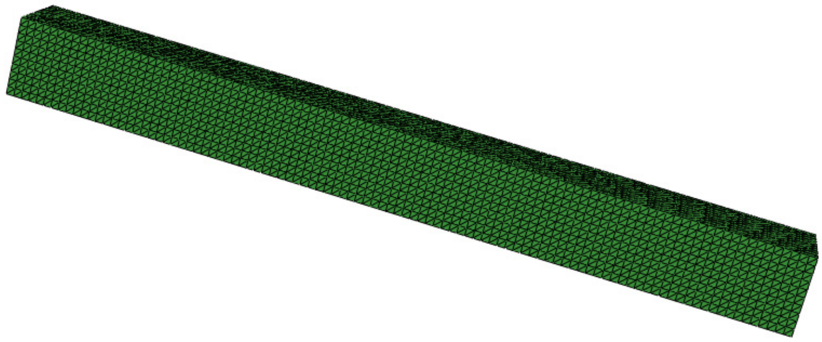
- steel strain;

- The strain corresponding to the yield strength of the steel;

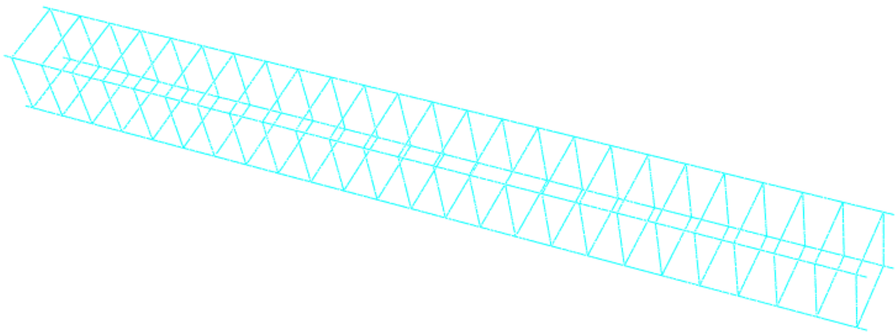
-The elastic modulus of steel;

- Steel yield strength.

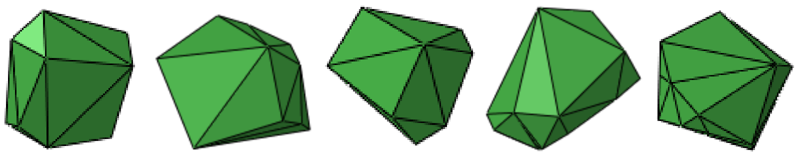
2.3. Establishment of Finite Element Model



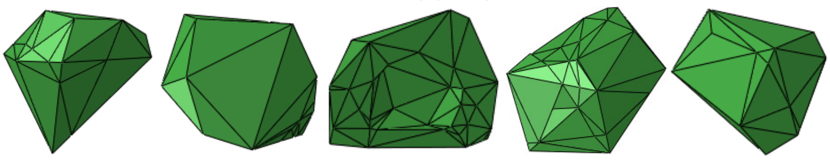
(a)concrete



(b)steel reinforcement



(c)aggregate



(d)Interface transition zone

Fig 5. Mesh division of each component

(1) Definition of contact surface

Since the research focus of this chapter is compression analysis, that is, the bond-slip relationship only considers the longitudinal tangential behavior, and the linear friction coefficient of the bond-slip effect between steel and concrete is set to be 0.8.

(2) Unit type selection

C3D6 is used in the whole concrete; stirrups and longitudinal bars adopt two-node linear three-dimensional truss element T3D2.

(3) Grid division

In the process of component meshing in this chapter, structured meshing technology is adopted. The global size of the overall grid is set to a maximum of 20 mm, and the minimum grid size is set to 2 mm.

(4) Boundary conditions and loading methods

In order to simulate the fixed support conditions of the column bottom, a reference point RP3 is arranged in the center of the column bottom and coupled to the entire column bottom surface, and then fixed constraints are applied to RP3 (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0). Through this setting, the fixed constraint on the bottom of the column is realized, that is, the displacement and rotation of the RP3 point are limited to zero.

In order to simulate the case of applying axial compression to the structural section, in the defined load module, the pressure is selected and the required value is input. Then the top of the column is selected as the cross section of the applied pressure, and the applied direction is set to be vertical and uniform loading.

(5) Solution Settings

The incremental iteration method is selected to solve the problem, and the automatic incremental step size method is used to solve the problem. This method can make the calculation of the model tend to converge more easily.

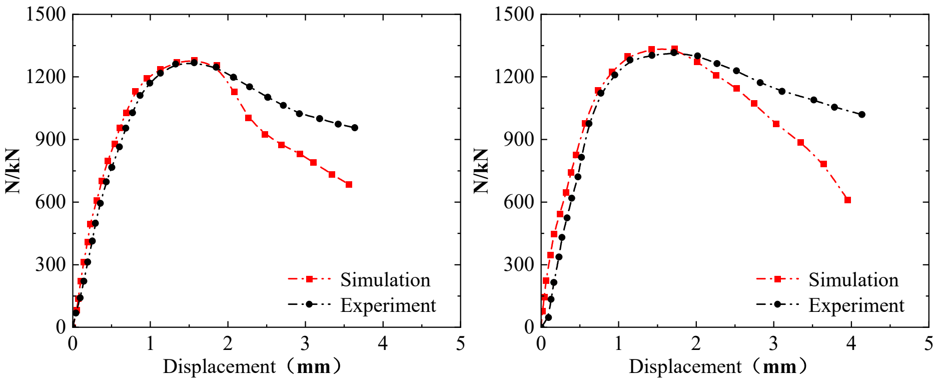
2.4. Model Validation

Two RC column specimens (RC-1 and RC-2) from literature [12] were simulated (Table 2). Load-displacement curves (Figure 6) and ultimate bearing capacities (Table 3) showed close agreement between simulations and experiments.

Table 2. Material parameters of RC columns

Specimen number	Steel bar diameter/ mm	Stirrup diameter/mm	Specimen size/mm (D×B×H)	Concrete grade	Rebar Grade	Stirrup grade
RC-1 [12]	10	8	180×180×650	C50	HRB400	HRB400
RC-2 [12]	10	8	180×180×650	C50	HRB635	HRB635

2.4.1. Comparison of Load-Displacement Curves



(a)RC-1 (b)RC-2

Fig 6. Comparison of load-displacement curves between simulation results and test results

In order to evaluate the performance of the finite element model constructed in this chapter in terms of calculation accuracy and ultimate bearing capacity prediction, the load-displacement curves of the two groups of specimens were compared with the simulated corresponding curves. The detailed comparison results are shown in Fig.6.

It can be seen from Fig.6 that the simulation curve and the test curve are in good agreement in the rising stage, which indicates that the two have good consistency in describing the bearing capacity of the specimen. In the decline stage, although there is a certain degree of difference, the development trend of the two remains similar.

2.4.2. Comparison of Ultimate Bearing Capacity

The comparison between the experimental data of each specimen recorded in the existing literature and the simulation data of the model established in this chapter is shown in table 3. The results show that the simulated values are close to the experimental values.

Table 3. Comparison of test results and simulation results

Specimen number	simulation value/kN	test value/kN	simulation value/test value
RC-1 [12]	1299	1268	1.02
RC-2 [12]	1360	1320	1.03

3. Conclusion

In this chapter, Python language is used to program a program that can quickly and efficiently establish a program that includes the mesoscopic components of concrete (including aggregate, cement mortar and interfacial transition zone), and ABAQUS finite element software is used to establish the mesoscopic numerical model of RC columns. The main conclusions are as follows:

(1) The shape of polyhedron aggregate established by Python language is consistent with the real aggregate, and the final distribution state of polyhedron aggregate conforms to the mesoscopic numerical model of concrete.

(2) Based on the mesoscopic numerical model of RC column constructed by ABAQUS finite element software, the mechanical behavior of the specimen under compression is effectively simulated. The predicted results of the load-displacement curve and the ultimate bearing capacity provided by the model are in good agreement with the actual RC column compression test data, which confirms the feasibility of the model.

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