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Research Article

Structural Assembly Analysis of Concrete Buildings with Intelligent Finite Element Analysis

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In recent years, with the rapid development of China's construction industry, assembled buildings have become more and more common. In this context, China attaches great importance to the development of assembled buildings and has introduced a series of policies to support the promotion of assembled buildings. Assembled building technology has become relatively mature in some developed countries. From their experience, it can be learned that the construction of an assembled concrete structure technology system is the basis for the promotion of assembled concrete buildings. A factory-based production model enables prefabricated concrete elements to be produced to a good quality. The key to the technical system for the construction of assembled concrete structures is the connection of the prefabricated elements. At the same time, it is essential to consider not only the reliability of the structural performance of the assembled concrete structure but also the cost and safety of the design, production, transport, and construction processes. In fact, the safety of an assembled concrete structure depends to a large extent on whether the nodal connection technology meets the design and quality requirements. Unlike conventional cast-in-place concrete structures, the key nodes of assembled concrete structures have a greater impact on the mechanical properties of the load transfer. In other words, this influence is directly related to the design of the prefabricated elements. Hence, the mechanical properties of precast nodal joints, such as good stiffness, are essential for the structural safety of assembled buildings. In the case of assembled buildings, the correct form of nodal connection is decisive in ensuring that the connection meets the design and service requirements. In addition to this, the correct nodal connection form will ensure that the design life is maintained. The uneven quality of many prefabricated components has limited the promotion of assembled concrete structures and is a key constraint to their development. At this stage, there are no uniform standards for quality control systems and measures on site in China, and the level of technical management is not yet fully mature. What is more, the overall quality of construction personnel is not high enough, which might lead to some frequent issues with the quality of connections in the field during the actual construction process. As a result, the development of assembled concrete structures urgently requires perfect construction management standards as a guide for on-site joint construction, so as to guarantee the quality level of on-site joint construction. In order to study the force performance of assembled concrete structures, this paper establishes an analytical model for assembled concrete buildings based on the intelligent finite element method. To be specific, this research introduces artificial neural network theory into the structural analysis of assembled buildings and transports it into the finite element solution, thus forming an intelligent finite element method.

1. Introduction

An assembled concrete structure is a concrete structure made of prefabricated elements, which are assembled and connected [1]. To be specific, an assembled concrete structure can be fully or partially prefabricated and is a form of industrialised building production through assembly. This type of assembled building structure has been widely used in many foreign countries. Due to its stable quality, high production efficiency, and environmental protection, assembled concrete structures are increasingly attracting the attention of real estate developers, building construction companies, and designers in China [2]. At the same time, assembled concrete structures are not only an emerging green and energy-saving building structure but also an effective way to achieve sustainable development in housing construction [3]. The assembled building system transforms the traditional on-site work into a factory-based production system, enabling the construction of buildings to gradually enter the modernisation path of industrialisation, information technology, and intelligence [4]. As China's economic and social development and industrial transformation and upgrading accelerate, the need for modernisation of the construction industry becomes increasingly urgent and the vigorous development of assembled buildings becomes an inevitable choice [5]. As can be seen in Figure 1, from 2016 to 2021, the average annual growth rate of new construction floor area for assembled buildings in China was as high as 40%. Therefore, in order to achieve the development goal of assembled buildings, assembled concrete buildings must be the mainstay.

The assembled structure system should be viewed from two perspectives. On the one hand, assembled structures have the advantages of high production efficiency and short construction periods [6]. The combination of modern concrete construction technology and traditional assembled concrete construction technology can therefore bring the advantages of assembled construction technology into full play, thus further promoting the development of assembled construction technology [7]. On the other hand, the nodes of assembled concrete are less integral, more difficult to transport and install, and more difficult to design than cast-in-place concrete [8]. In addition to this, assembled concrete nodes have been found to be the weakest of the frame structures in the world's major earthquakes, with serious breakage of the nodes [9]. For instance, Figure 2 illustrates the seismic damage to an assembled concrete frame structure during an earthquake. For the construction of assembled concrete buildings, component design is an important part of the design phase [10]. Component design plays a key role in controlling the cost and construction cycle of an assembled building [11]. Therefore, the quality of the assembled concrete is at the heart of the design work during the component design phase. The component design is not only for laminated slabs and beams but also for beam-column nodes, beam-slab nodes, beam-beam nodes, and other nodal connections in assembled frame structures [12]. The design of assembled concrete structures involves a large number of mechanical designs and calculations. Compared to conventional structural design, the design of structural elements such as columns, beams, and slabs is more demanding, complex, and influential than traditional structural design [13].

In addition to this, component splitting is also a key aspect of component design. Usually, component manufacturers split the design drawings in order to facilitate the lifting of the components by the constructors. However, in the process of dismantling, they often neglect to verify and analyse the load-bearing properties [14]. As a result, the strength of the jointed parts is reduced in relation to the design strength during the actual dismantling process [15].

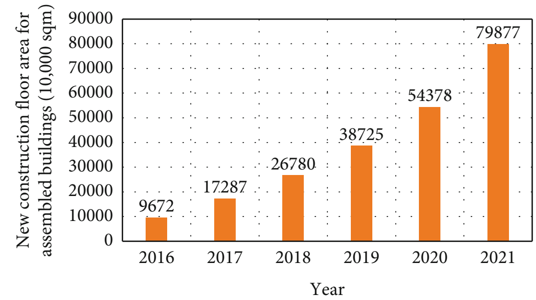

Figure 1: New construction floor area for assembled buildings in 2016-2021 in China.

To a certain extent, these objective factors reflect the fact that the technical system for design, dismantling, and construction in China is not yet complete, that standards and specifications are not yet comprehensive, and that the level of management needs to be improved. At the same time, there are very few design institutes that have the capacity to design mature assembly-type buildings [16]. At this stage, most design institutes are still in their infancy, and their technical systems for the design and disassembly of shaped prefabricated components are not perfect, and their experience is not yet mature. To be specific, their production capacity for shaped components does not meet the requirements of the construction site. In addition, there is a disconnect between the dismantling effect and the capacity and efficiency of the component manufacturers, which makes it difficult to produce on a rapid scale [17]. After all, component factories are more likely to disassemble simple prefabricated nodes for common applications. As a result, these problems can lead to prefabricated elements that are not fully compliant with the design requirements and can even affect the load-bearing properties of the elements.

China's concrete assembled buildings originated in the 1960s, and through independent research and foreign imports, a series of concrete assembled building systems gradually emerged. At that time, single-storey industrial buildings and multistorey frame buildings were typical types of assembled concrete buildings [18]. In the 1980s, the development of assembled concrete buildings in China reached a climax with the establishment of tens of thousands of prefabricated concrete plants throughout the country, with an annual output of 30 million sqm. In the late 1980s, the domestic construction market demand increased dramatically. However, the load-bearing capacity and ductility of domestically produced precast elements were low. Building systems using precast concrete elements did not solve the problems of waterproofing and thermal insulation well [19]. In the Tangshan earthquake, the damage to a large number of buildings using precast concrete elements revealed the lack of seismic performance of domestic assembled concrete buildings. In addition, due to the rise and promotion of commercial concrete, assembled concrete structures are gradually being replaced by cast-in-place concrete structures [3].

The fundamental reason for the decline in the development of assembled concrete buildings in China in the last

Figure 2: Seismic damage to an assembled concrete frame structure during an earthquake.

century was the low level of industrialisation and the lack of a mature technical system for assembled concrete structures. In addition to this, the quality control mechanism in the domestic market was not perfect [20]. From the experience of developed countries and regions, assembled concrete buildings can fully meet the safety and functional requirements of buildings and have many advantages over cast-in-place concrete buildings. In recent years, with the rapid development of China's economy and society, the demand for industrialisation of the construction industry has emerged. At the same time, the quality control mechanism of the construction market in China is gradually maturing, and the development of assembled concrete buildings has become an inevitable trend [21]. At present, China's market share of assembled buildings is relatively low, and in order to vigorously promote assembled buildings, there is an urgent need to develop a series of assembled concrete building technology systems that are in line with national conditions. In 2020, public buildings will account for 33.2% of the new construction of assembled buildings in China. In public buildings, especially schools, hospitals, and government institutions, concrete frame structures play an important role. Therefore, it is of great importance to study the technology of assembled concrete frame construction.

The structural elements of assembled concrete buildings are produced in the factory [22]. As a result, these structural elements perform better in terms of load capacity, stiffness, and ductility. The connections between prefabricated elements can be made either dry or wet, which is different from conventional monolithic cast-in-place concrete structures [23]. There are doubts in the country about the integrity of the connections, particularly in terms of their seismic performance. The damage mechanisms of frame structures under seismic action are beam-hinged, column-hinged, and mixed-hinged mechanisms (see Figure 3). The ideal damage mechanism is either the beam-hinged damage mechanism or the mixed-hinged damage mechanism, both of which are based on the formation of plastic hinges at the beam ends and first floor columns. The key to the study of the construction technology of assembled concrete frame structures is therefore the study of the seismic performance of the nodal connections.

In recent years, with the continuous development of computer technology and information technology, numerical calculation methods represented by the finite element method have been rapidly developed and widely used in construction engineering. The finite element method can effectively solve practical problems that are difficult to solve with traditional calculation methods for assembly buildings [24]. It is worth noting, however, that although these numerical methods have successfully solved a large number of complex engineering problems and can be used to simulate the force characteristics of assembled structures by quantitative means, they must be based on a sound understanding of the material properties [25]. Only if the calculation model is sound, and the material ontology model and the calculation parameters are accurately given, can the numerical results be correct and reasonable.

The traditional method of analysing the structure of an assembled building is usually to obtain test data through some geotechnical experiments or field tests and then to analyse the test data using various data processing methods such as statistics and regression [26]. The data is then analysed using various data processing methods such as statistics and regression. The laws are then identified and fitted to the simulation using mathematical expressions. Under certain assumptions, a few material parameters are determined, the model is extended to any stress condition, and new test results are used to test and modify the model [27]. Based on this, the following problems arise. On the one hand, the complex properties of assembled building materials require complex mathematical models and a large number of material parameters to express their complex physical and mechanical properties. This makes it difficult to determine the parameters and to use the model. On the other hand, if some assumptions are made, a certain amount of error is bound to be introduced during the numerical calculations. The magnitude of this error is difficult to estimate theoretically and needs to be verified using a large number of examples. It appears that although a large number of analytical models have been proposed for the different characteristics of assembled buildings, these models are mostly simple approximations of the physical and mechanical characteristics of the building materials. In other words, it is difficult to fully express the complex nonlinear properties of assembled buildings, which has forced the application of new theories and methods to the analysis of assembled building structures.

The theory of artificial neural networks, which is based on many modern sciences such as brain neuroscience [28] and machine learning, is self-learning, self-organising, and self-adaptive. Therefore, artificial neural networks have excellent characterisation capabilities for highly nonlinear problems. This study investigates the creation and use of neural network models and how they can be applied to the finite element method to form intelligent finite element

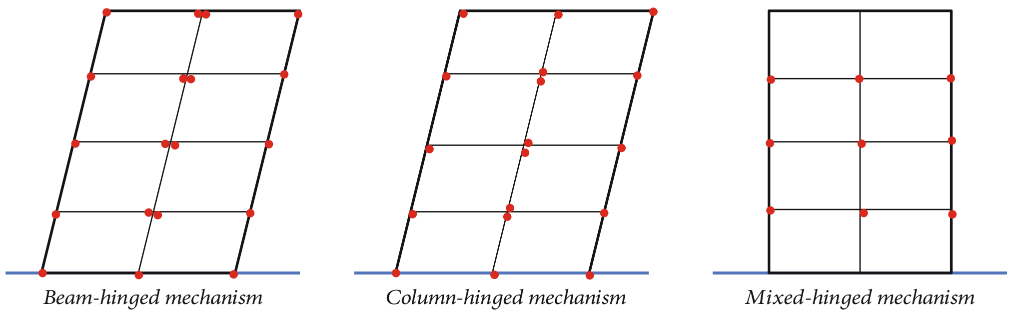

Figure 3: Mechanisms of damage to the frame structure.

methods. After that, this research applies the intelligent finite element method to model the building structure and analyse the assembled components to verify the accuracy of the model. At the same time, parametric analysis of the assembled frame structure is carried out to investigate the relationship between the assembled structure and the overall forces of the cast-in-place structure.

2. Intelligent Finite Element Analysis

The finite element method is an effective numerical calculation method that has developed rapidly in recent years. The basic idea is to discretize a continuous structure into a finite number of cells and to set a finite number of nodes in each cell, considering the continuum as a collection of many cells connected at the nodes. At the same time, the nodal values of the field functions are chosen as the fundamental unknowns and an interpolation function is assumed in each cell to represent the distribution pattern of the field functions in the cell. As a result, the variational principle in mechanics can be used to establish equations to solve the discretized finite degree of freedom problem. The cell can be designed in different geometries, allowing flexible modelling and approximation of complex solution domains. As the number of cells increases, the accuracy of the solution increases and eventually converges to an exact solution if the interpolation function meets certain requirements.

The finite element method is one of many numerical analysis methods, each with its own scope of application (see Table 1). However, in terms of the degree of application, the finite element method is the most commonly applied.

2.1. Principle of Finite Element Analysis. The finite element method is based on the energy principle. For different problems, the finite element method can take different forms of formulation. They are equivalent to each other and have their own scope of application. The interrelationship of the energy principles is shown in Figure 4.

In order to be able to represent cell displacements, strains, and stresses in terms of nodal displacements, certain assumptions have to be made about the in-cell displacements. This means that the distribution function of the in-cell displacements is interpolated using the cell nodal displacements, as shown in

$$v = M \times n^g, \tag{1}$$

where v refers to the displacement vector, M indicates the displacement difference matrix, and n^g is the unit node displacement vector.

From the principle of virtual work, the equilibrium equation for the unit can be derived, as shown in

$$f^g = l^g \times n^g, \tag{2}$$

where l^g refers to the stiffness matrix and f^g is the equivalent nodal force.

The Newton-Raphson method is one of the best-known methods for solving nonlinear systems of equations. For a linear equation in one element,

$$\Psi(i) = n(i)i - f = 0. \tag{3}$$

Then, the Taylor expansion of $\Psi(i)$ at i_0 is

$$\Psi(i) = \Psi(i_0) + \Psi'(i_0)(i - i_0) + o(i - i_0). \tag{4}$$

After that, removing the higher-order terms can yield

$$i = i_0 - \frac{\Psi(i_0)}{\Psi'(i_0)}. \tag{5}$$

The iterative solution process is shown in Figure 5.

2.2. Artificial Neural Network. The most complex and developed organ in the human body is the brain. The brain is the control centre for all human thought, the command centre for all kinds of reactions, and the material basis for higher neural activity. Scientists are constantly exploring the brain and envisaging the creation of a machine system that can mimic the brain's thinking and actions. This would replace the human brain in certain areas and reduce the amount of human work. In order to simulate the thinking and control of the human brain, a simplified mathematical model has been created based on the biological principles of the human brain, using physical and mathematical methods to simulate and abstract the biological workings of the human brain.

In terms of the transmission of information, the dendrites of a nerve cell receive signals from other nerve cells at the synapse. These signals may be either excitatory or inhibitory. The signals received by all dendrites are transmitted to the cell body for integrated processing. If the amount of excitatory signals received by a cell during a time interval

Table 1: Different numerical analysis methods.

Numerical analysis method	Basic principle	Solution way	Application
Finite element method	Minimum heat principle	Solving systems of equations	Inhomogeneous materials
Boundary element method	Betti's reciprocity theorem	Solving systems of equations	Small deformation materials
Discrete element method	Newton's theorem of motion	Explicit difference	Large deformation materials
Lagrangian yen method	Newton's theorem of motion	Explicit difference	Homogeneous materials

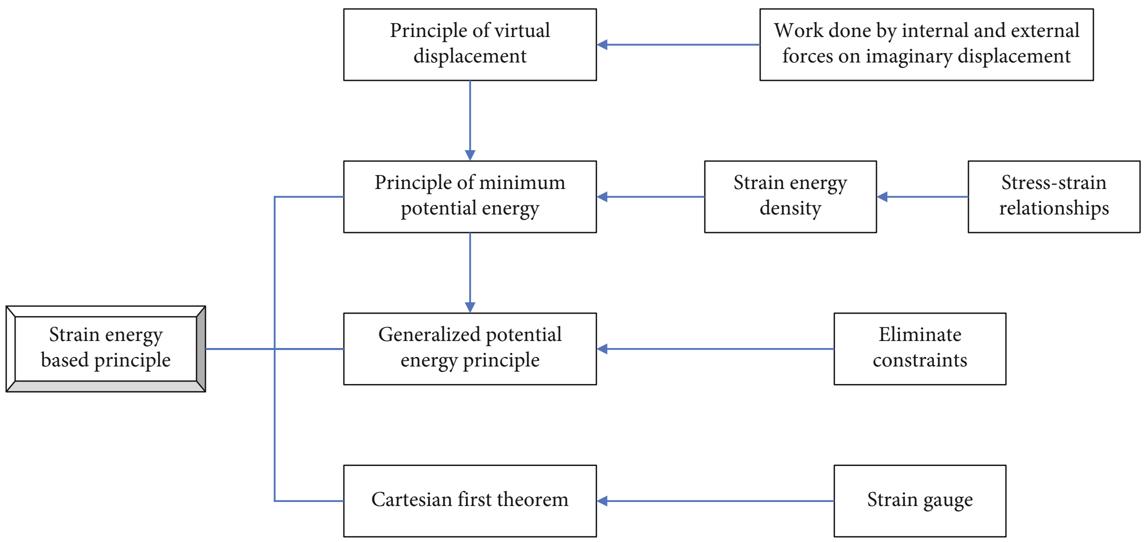

Figure 4: Interrelationship of the energy principles.

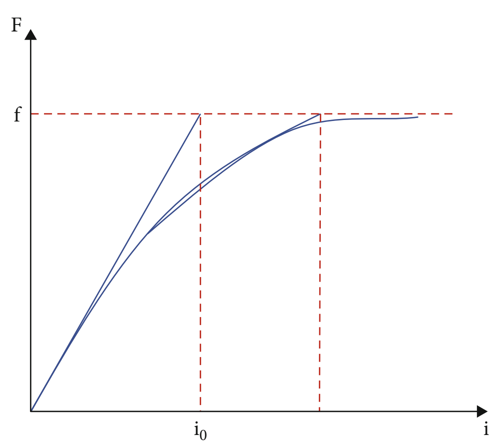

Figure 5: Iterative solution process.

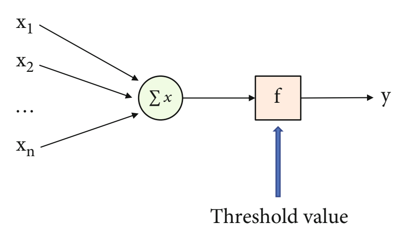

Figure 6: Typical artificial neuron model.

is large enough to activate the cell, a pulse signal is generated. After that, this signal is transmitted along the axon of the cell and through the synapse to other nerve cells. By abstracting and simplifying biological neurons, artificial neuron models have been proposed, and a typical artificial neuron model is illustrated in Figure 6.

In neural network algorithms, the learning rate is defined as a constant. If it is given too low a value, the network learns slowly and the number of training sessions increases. If it is given too high, however, the training will oscillate and fail to converge. In practice, it is difficult to determine an optimal learning rate that is always appropriate in the network learning process. The adaptive learning rate method involves changing the value of the learning rate throughout the training process, depending on the actual network training situation. Thus, an adaptive learning rate adjustment system can be defined. When the weights are adjusted by the same amount twice in a row during the training process, the adjustment is too small. In this case, the learning rate can be multiplied by an adjustment factor greater than 1 to speed up the adjustment of the weights. When two consecutive weights are different, the weights are overadjusted and the learning rate should be reduced. Therefore, the learning rate can be divided by an adjustment factor greater than 1 to reduce the amount of correction to the weights, thus reducing the oscillations in the network.

2.3. Principle of Intelligent Finite Element Analysis. The basic idea of the intelligent finite element method is to replace the conventional instantonal model with a neural network

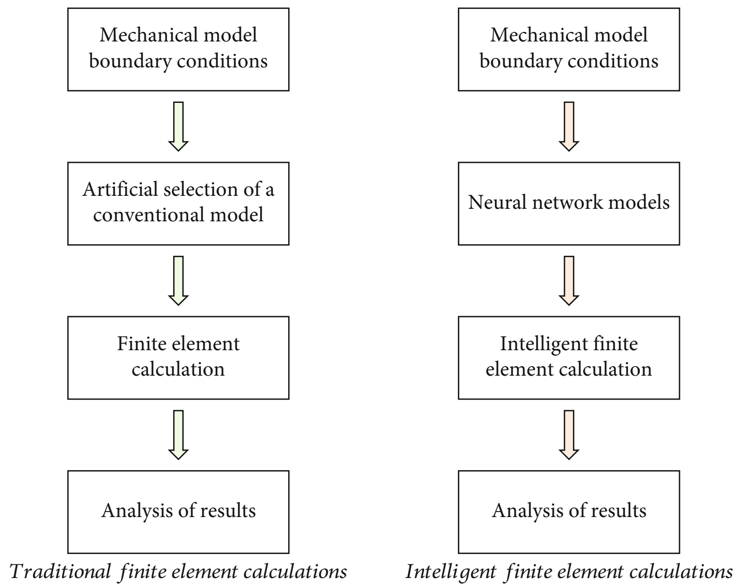

Figure 7: Difference between the two finite element methods.

instantonal model and use it in finite element calculations. Figure 7 shows the difference between the two finite element methods.

The adaptive intelligent finite element method calculations are carried out according to the incremental method. The stiffness matrix in each incremental step is calculated according to the conventional finite element calculation, similar to the elastoplastic nonlinear finite element method. The initial displacements of the units are solved iteratively by Newton's method, the strains are derived from the geometric equations and the stresses of the units are mapped using a trained neural network intrinsic model. As the displacements and strains in the structure are not realistic at this point, the stresses mapped by the neural network are also not realistic. The stresses mapped by the neural network are not the real stress field, and therefore, there are unbalanced forces, which are used as control criteria to iterate the solution. As the neural network, intrinsic structure model can characterise the real material intrinsic structure relationship, the reiterative solution should result in improved displacements. This cycle is repeated until the error tolerance is met. Finally, the real displacement and stress fields in the structure can be calculated. The entire solution process embeds the neural network into the finite element calculation and adaptively completes the solution, resulting in an adaptive intelligent finite element method.

3. Structural Assembly Analysis of Concrete Buildings

In this study, a three-dimensional nonlinear finite element analysis of the assembled concrete frame nodes was carried out using an intelligent finite element analysis method. In addition, the seismic performance of the assembled frame nodes is analysed by using interface springs to simulate the force performance of the vertical laminated surfaces of the assembled concrete joints. Based on this example, the finite element calculation parameters applicable to the analysis of the assembled frame nodes are validated, and the experimental studies on assembled concrete conducted by other scholars are also validated. After that, a parametric analysis is carried out to compare the seismic performance of frame nodes with floor slabs with that of simple assembled beam-column nodes. This can provide some theoretical reference for the design and construction of assembled frame nodes in practical projects.

3.1. Connection between Units. The shear capacity of a vertical stacked beam with a vertical stack of old and new concrete at the end of the column is generally composed of three parts: the compressive shear capacity, the shear capacity of the shear key, and the shear capacity of the reinforcement pins. After treatment of the old and new concrete, the slip of the vertical laminated surface is minimal even at high shear forces. Therefore, the seismic performance of a laminated beam with a vertical laminated surface is similar to that of a cast-in-place beam.

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The assembled monolithic concrete frame structure is a combination of cast-in-place columns and precast beams. The bonding strength of the old and new concrete has a significant influence on the load-bearing properties of the assembled concrete nodes. In general, the axial tensile strength of the bond is 70% of the axial tensile strength of

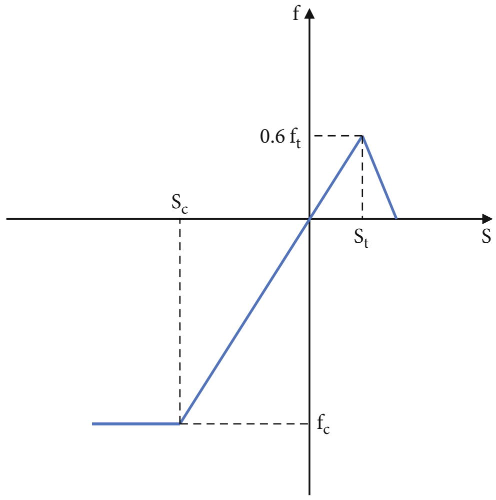

FIGURE 8: Normal force versus displacement of nodal springs in the finite element model.

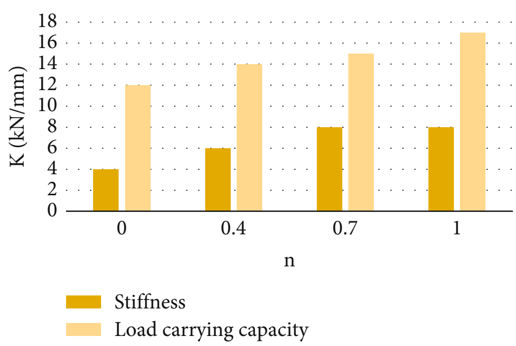

FIGURE 9: Stiffness load capacity with different tensile strength factors.

the new concrete as a whole. This indicates a reduction in strength due to the presence of the bonding surface. Within a certain range of roughness, the greater the roughness, the higher the axial tensile strength of the bond. For this reason, in general assembled concrete, the bonding surfaces of old and new concrete are made as rough and clean as possible in order to ensure that the old and new concrete work well together.

3.2. Tensile Strength Factor of Old and New Concrete. The tensile strength coefficients for old and new concrete range from 0 to 1. A coefficient of 1 is generally considered to approximate cast-in-place concrete construction. When 0 is taken, the tensile strength of the concrete at the joint of the old and new concrete is not considered. The results for the stiffness load capacity with different tensile strength factors are shown in Figure 9. As can be seen, when the tensile strength factor is 0, the node stiffness decreases significantly and the load-carrying capacity also decreases significantly. As the tensile strength factor increases, the node stiffness and load-carrying capacity also increase. When the tensile strength factor is 0.7-0.9, the load-displacement curve of the node does not change much and the stiffness and load-carrying capacity do not change significantly.

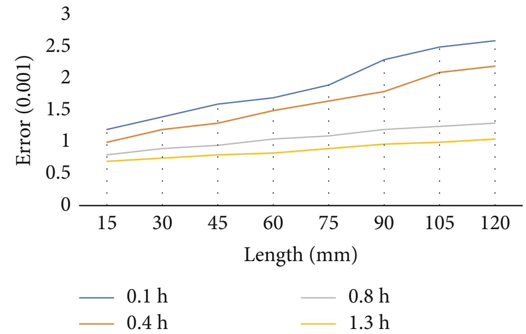

FIGURE 10: Strain diagram of the casing.

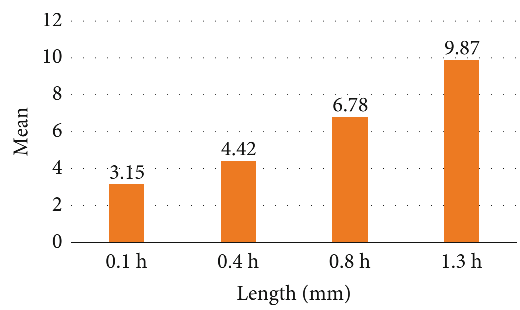

FIGURE 11: Nodal ductility for different casing lengths.

Nodal damage is the main form of damage in assembled structures, so there is an urgent need to strengthen the research on new nodes. Optimisation of the node configuration will enable the tensile strength coefficient of the old and new concrete joints to reach a level comparable to that of cast-in-place structures. At the same time, the strength performance of the nodes will not lag behind that of cast-in-place structures.

3.3. Casing Connection Length. Figure 10 illustrates the strain diagram of the casing, which shows the variation of the casing strain during loading of different casing lengths. As can be seen from the graph, the casing strain decreases with increasing length. When the length exceeds the height of the beam h, the casing strain does not change significantly. Therefore, the casing is within the height of the beam, which reduces the strain on the reinforcement in the casing and increases the deformation capacity of the structure.

Figure 11 shows the nodal ductility for different casing lengths. As the length of the casing increases, the ductility of the node also increases. When the length of the casing exceeds the height of the beam, the change in ductility remains more or less constant.

4. Conclusion

As China's technological strength continues to advance and the level of information technology in construction continues to improve, the drawbacks of traditional construction production methods are becoming more and more prominent. In the course of the development of the construction industry, modular construction will become the inevitable development of modernised and industrialised construction in the new era. The advantages of assembled construction over traditional construction are obvious, as it not only reduces the waste of construction resources but also reduces environmental pollution. As a result, assembled buildings have begun to lead the way in the construction industry. However, a great deal of research and practical experience in engineering projects shows that China is generally late to the party in assembling buildings. Specifically, the development of assembled buildings has been slow, and standards and technical systems have been studied late. For the time being, a relatively complete set of technical standards and systems has been initially developed for the connection of assembled concrete structures. However, there are some outstanding problems with the nodal connections of assembled concrete structures in China. For example, the quality control specifications and control system are not mature enough. A reasonable form of connection for assembled concrete structures is essential to ensure structural integrity and reliability, and the nodal connection is a key technical issue in the development of assembled buildings. However, there is currently no comprehensive and complete system of standards for the nodal connections of assembled concrete structures. Therefore, this study is aimed at improving the development of assembled buildings with the help of intelligent and effective elemental methods and at promoting the rapid development of the industrialisation of construction.

Based on the findings already presented in this paper, there are several points where future work can continue in depth. Due to the limitations of the test equipment, the loading of the nodal specimens did not meet the expectations. The study of the specimens in this paper is mainly qualitative, and the seismic performance of the nodal specimens, especially the strongly connected specimens, during large displacements in the late loading period is yet to be studied.

Data Availability

The labeled dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no competing interests.

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