State-of-the-art of Research Progress of Self-centering Structure System

Qian Zhang¹, Ergang Xiong*², Ruie Guo³,
¹School of Human Settlements and Civil Engineering, Xi’an Euraisa University, Xi’an, Shaanxi, 710065, China
²School of Civil Engineering, Chang’an University, Xi’an, Shaanxi, 710061, China
³Gaoxin College, Xi’an University of Science and Technology, Shaanxi, 710061, China
*Corresponding author’s e-mail: xerg@chd.edu.cn

Abstract: Traditional building structures dissipate seismic energy through the plastic deformation of members in the earthquake, which may lead to a large residual deformation after the earthquake. Those structures are very difficult to repair. Traditional building structure can become a new structure with self-centering ability by using a special energy dissipation component, adding prestressed tendons or supplementing dampers. Compared to the traditional building structure, this new self-centering structure can more effectively reduce the residual deformation caused by the earthquake, and it has a desirable capability to dissipate seismic energy so as to enable itself to be of more security. In this study, the domestic and foreign self-centering structures are classified and summarized. This study deals with research progress of self-centering structures including self-centering concrete shear wall structure, self-centering concrete frame structure, self-centering steel moment frame structure, self-centering braced steel frame structure, self-centering steel plate shear wall structure and self-centering offshore platform structure. Besides, this study introduces the related research progress of other research fellows

1. Introduction
In recent years, earthquakes have brought huge losses to human life and property, and the root cause of the losses is mostly caused by the collapse of buildings, so the design of a structure with good seismic performance has become the top priority in the design of building structures. The reason why the traditional structure is seriously damaged by the earthquake is that the structure has large residual deformation after the earthquake, and it is difficult to recover after the deformation, and it is also difficult to repair. In recent years, scholars at home and abroad have devoted themselves to the research of earthquake resilient structure that can recover by themselves after structural deformation after earthquakes. Reusable functional structure refers to the structure that can restore its functional function without repair or minor repair after earthquake. There are several ways to achieve it in structural form, for example, the replaceable structural member can quickly restore the function of the structure after earthquake; the adoption of the self-centering structure can permit the structure automatically restore to the normal state of the structure, reduce the residual deformation of the structure after earthquake; Rocking wall or rocking frame was used to reduce structural damage, allowing it to be put into use with little or no repair after the earthquake. These methods are not completely independent, sometimes two
or even three methods can be combined for design.

This paper mainly summarizes the research progress of self-centering structures at home and abroad in recent years, and introduces the research status of self-centering concrete shear wall structures and self-centering concrete frame structures respectively.

2. Research status of self-centering structural systems at home and abroad

2.1. Self-centering concrete shear wall structure

In 1999, Kurama et al.\[1\] proposed the unbonded prestressed concrete self-centering shear wall structure system. It consists of a reinforced concrete shear wall and a built-in vertical unbonded prestressed steel strand. The wall is not firmly connected to the foundation. Under horizontal load, the wall can rotate around the central axis to provide restoring force through the prestressed steel strand. The system shows good seismic performance and self-centering ability. Kurama\[2\] added energy dissipation devices to the above self-centering shear walls to enable the structure to dissipate energy when deformed laterally. In 2007, Restrepo and Rahman\[3\] further improved the above self-centering shear wall by adding a kind of soft steel reinforced damper between the wall and the foundation, which can consume energy through the plastic deformation of the soft steel when the wall has a certain lateral deformation. Henry et al.\[4\] established an end-column self-centering shear wall model with O-type energy-dissipation connectors through finite element software, and analyzed the relationship curve of lateral force and displacement, stress of unbonded prestressing tendon, compressive strain of concrete, and deformation of connectors, etc., which were in good agreement with the test conducted by Tweigden et al.\[5\]. The connection between the shear wall and the floor slab is analyzed. When the prefabricated shear wall is rigidly connected with the floor slab, the floor slab will be damaged under the action of earthquake. However, the vertical displacement separation of the floor slab and the shear wall with O-type connectors can effectively reduce the damage of the floor slab in the process of rocking and lifting of the shear wall.

In our country, Ma Xin and Lv Xilin using the finite element software ABAQUS to the centering shear wall model to simulate low reversed cyclic loading, the analysis of the residual deformation of the structure, the maximal displacement, wall failure, since the restoration capacity, energy dissipation capacity, etc., analyzes the soft just damper number and length on the reduction and the influence of the shear wall since the centering. Hu Xiaobin obtained the horizontal force-angle curve of the self-reduction wall under reciprocating load through theoretical derivation, and deduced the conditions that should be satisfied to ensure the self-reduction performance of the self-reduction wall. The results showed that the self-reduction wall's deadweight and prestressing tendon jointly provided the self-reduction ability, and the damper provided the energy dissipation ability. The critical rotational load of the self-centering wall is related to the deadweight of the wall and the initial force of the prestressing bars. The residual deformation of the wall is related to the deadweight of the wall, the initial force of the prestressing bars and the yield force of the damper when the wall is completely unloaded. The damper yield force has the greatest influence on the hysteretic performance of the self-centering wall. Dang Xiangliang and Lu Xilin et al. conducted an experimental study on prestressed self-centering shear walls with horizontal joints at the bottom. The finite element simulation of solid element, plane stress element and thin shell element of a pseudo-static test of a self-centering shear wall was carried out by using ABAQUS software and compared with the test results. Results showed that the opening at the bottom of the prestressed horizontal seam, since the centering shear wall specimens have better since the centering ability and energy dissipation capacity, the finite element simulation method can well reflect the centering the hysteretic performance of prestressing shear wall, unbond prestressed reinforcement stress and the strain of concrete indicators, such as verified in the analysis of dynamic explicit shell element is adopted to improve the feasibility and rationality of structure simulation. Zhao Jun and Zhao Qi et al. carried out low cyclic load tests on 1 reinforced concrete shear wall and 4 shear walls with carbon fiber reinforced polymer (CFRP) bars, and the test analysis showed that the shear wall could have excellent self-centering performance if the CFRP bars were reasonably allocated in the shear wall.
2.2. Self-centering concrete frame structure

In 1993, Priestley and Tao [6] proposed the use of partially unbonded prestressed reinforcement self-repositioning precast concrete frame structure system as one of the main lateral force resistance systems in earthquake areas. The structure allows the frame beam to rotate in the prefabricated frame structure, and the frame beam is connected to the frame column through prestressed tendons. The ground motion energy is consumed by allowing a certain rotation at the contact surface of the beam and column. Macrae and Priestley, Stanton et al. then carried out an experimental study on precast beam-column joints. Stanton et al. used both soft reinforcement and unbonded prestressed steel bars at key joints. Soft reinforcement can be used to dissipate seismic energy.

Cheok and Lew [7] carried out low-cyclic cyclic load tests on 8 prestressed rotational joints of reinforced concrete frames, and the test results showed that the failure of the 8 joints was shown as post-tensioned prestressed tendon yield, concrete crushing on contact surfaces, and beam-column joint area opening. In 1996, Priestley and Macrae [8] conducted an experimental study on the seismic performance of unbonded prestressed self-centering reinforced concrete frame joints. In 1999, El-Sheikh et al. [9] carried out Pushover analysis and time-history analysis of 6-story unbonded prestressed self-centering reinforced concrete structures, and the fiber model and spring model proposed can be used for the analysis of such structures. In 2007, Morgen et al. [10] conducted an experimental study on the unbonded prestressed concrete frame with friction damper. In this paper, a design process is proposed to determine the friction force of the damper and the area of the prestressed tendons to meet the design strength and energy consumption requirements of the frame with given beam-column size. Through the nonlinear cyclic loading analysis of 8 integral frame systems, it is proved that the design of the whole structure can meet the predetermined strength and minimum energy consumption requirements through the above process.

Ye Lieping et al. of Tsinghua University also used the elastic reduction ability of high-strength unbonded steel bars to realize the post-earthquake self-reduction of concrete structures, and carried out experimental research and theoretical analysis. Zhang Xin et al. conducted seismic performance tests on concrete frames equipped with high-strength steel strand under low cyclic horizontal action, and the results showed that the high-strength steel strand had relatively strong self-centering ability, and the residual deformation of the structure after the earthquake was significantly reduced compared with that of ordinary reinforcement. Lv Xilin et al. conducted a shaking table test on the self-reduction reinforced concrete frame structure, and the test study showed that the self-reduction reinforced concrete frame structure had good ductility and deformation ability under the action of large earthquakes, and basically had no residual deformation after the earthquake. Han Jianping and Chen Jun used the general finite element software to study the bending moment and Angle characteristics of the self-centering joint of unbonded post-tensed precast reinforced concrete, and the analysis results showed that this new type of joint had sufficient strength and stiffness, and had good self-centering performance.

Gao Wenjun and Lv Xilin used OpenSees finite element software to carry out numerical simulation of the test model framework, and proposed an effective simulation method for beam-column joints and column foot joints. Lu Liang and Xu Yingchao et al., based on the parameters identified by joint static tests, conducted nonlinear time-history analysis on the seismic performance of self-centering reinforced concrete frames by using the finite element method, and the results showed that the numerical simulation results were in good agreement with the shaking table test results. Cai Xiaoming and Meng Shaoping et al. conducted experimental research on the new self-reduction prestressed prefabricated side joints, the joints in the prestressed prefabricated frame and the joints in the cast-in frame, and studied the effects of semi-rigidity on the seismic performance of the prestressed self-reduction frame structure. Numerical study the static elastic-plastic performance since the restoration of prestressed precast frame, the results show that PTED node has good self centering capacity and energy dissipation capacity, the prestressing force since the centering precast frame of node damage mainly focus on the Angle of beam and column components are basic flexibility, and prestressed prestressed since the centering the residual deformation of precast frame node is less than the cast-in-situ nodes, The energy dissipation coefficient is about half that of the cast-in-situ joint. Zou Yun and Lin Hui et al. used the finite element software ABAQUS to...
calculate and analyze the monotonic loading and low-cycle reciprocating load of a precast concrete frame joint with self-centering function, and analyzed the influence of parameters such as tensile stress, number of prestressing tendons and reinforcement ratio on the seismic performance of the joints. Liu Jialiang and Xu Fuquan conducted shear performance tests on 18 self-centering prestressed concrete frame joints in 6 groups. The study showed that the shear bearing capacity of the joints was positively correlated with the axial force of the prestressed screw, and the size of the joint surface of the members had no obvious effect on the shear bearing capacity of the joints. The use of steel leg can improve the shear performance of the joint.

2.3. Self-centering flexural steel frame structure

In 2001, Ricles et al.\footnote{11} proposed a self-centering steel frame structure system, which adopted post-tensioned prestressed joints, which were composed of prestressed bars arranged along the web of the steel beam and Angle steel. The prestressed bars were anchored to the column flange, and the shear force was jointly resisted by the friction force on the surface of the beam and column and Angle steel. Under the action of strong earthquake, the Angle steel will enter the yield stage to dissipate the seismic energy, so after the strong earthquake, only the Angle steel at the joint needs to be replaced to continue to use. In 2002, Ricles et al. conducted a study on self-centering steel frame structures and carried out seismic tests on 9 large-proportion joints. The study showed that the performance of self-centering steel frames could reach the performance of welded steel frames at the initial stage of the tests, and no residual deformation occurred as the tests went on. In 2003, Garlock et al.\footnote{12} conducted cyclic load tests on Angle steels used for self-centering steel joints, and studied the effects of Angle steels on joint stiffness, strength, energy dissipation performance, low-cycle fatigue performance and joint failure mechanism by changing Angle steel size, bolt arrangement and some key geometric parameters (Figure1). A reasonable mathematical calculation model is given to predict the initial stiffness of Angle steel, the load required at failure, the post-yield stiffness and the unloading performance. The model is in good agreement with the experiment. In 2005, Rojas et al.\footnote{13}, based on the above research, introduced friction plates at the rotating joints of steel frame beam-column connection, which not only allowed the joints to rotate, but also made the joints dissipate energy by friction during rotation. At the same time, the calculation and analysis of the self-centering steel frame structure with 6-story and 4-span energy dissipation joints under strong earthquakes are carried out. The results show that the frame has good energy dissipation capacity, self-centering capacity and sufficient strength, and its seismic performance is better than that of the traditional welded steel frame structure. In 2005, Garlock et al.\footnote{14} conducted an experiment on six full-scale cruciform beam-column joints (inner joints). The effects of the initial prestress, the number of prestressed strand strands and the length of beam flange stiffeners on the failure modes were investigated. The test results show that, even under large cyclic loads (the displacement Angle between floors is up to 4%), the joint still has good self-repositioning ability, and avoids the local
buckling of the beam and the yield of the prestressed steel strand. In 2007, Gralock et al.\cite{15} studied the performance of the self-centering frame system, designed such nodes, especially the whole frame system based on the performance, proposed the design flow chart and the suggested formula of relevant parameters, and finally carried out nonlinear time-history analysis on a five-storey and four-span steel frame model. The results of time history analysis are compared with the design requirements, which proves the operability and effectiveness of the design process and design criteria.

Charles etc. has studied the reduction and the performance of the steel structure response under strong earthquakes, the results show that the reduction and framework of the relative displacement of each layer is lower than the traditional framework, the relative reduction and framework of the layers of residual displacement is less than the traditional steel frame, and the main structure failed to yield such as beam after the quake, proved that this new framework since the centering ability. Pan Zhenhua and Pan Peng et al. summarized and analyzed the self-centering new-shaped steel structure system and its mechanical characteristics, and the study showed that the self-centering steel structure system was effective and feasible in engineering. Zhang Shuai conducted time-history analysis on a three-layer welded steel frame and a three-layer post-tensioned self-centering frame, and the results showed that the tensioned self-centering frame had smaller inter-layer displacement than the welded steel frame during the earthquake, and almost no residual displacement after the earthquake, and the floor acceleration was much smaller than the traditional welded steel frame. Jiang Chengliang and Li Qicai compared the influence of the prestress of steel wire on the performance of self-centering steel frame through ANSYS simulation and test. The study showed that with the increase of the prestress of steel wire, the energy dissipation capacity of self-centering steel frame was slightly reduced and the self-centering capacity was significantly enhanced. Zhang Yanxia and Ye Jijian et al. used the finite element software ABAQUS to carry out static elasto-plastic analysis of a four-storey, two-span plane steel frame, and studied the seismic performance and self-centering performance of the whole self-centering steel frame structure with friction damper on the beam web, and discussed the influence of steel strength on the self-centering performance. The self-setting performance of self-setting steel frame structure is discussed. Han Jianping and Liu Shengwen studied the seismic performance of self-centering steel frames under low-cycle reciprocating loads, and analyzed the influence of initial prestress value and steel wire quantitative analysis parameters on the self-centering performance and energy dissipation capacity of the structure. Fang Youzhen and Yang Yonglong et al. studied the seismic performance of the joints in the new rolled PEC column-steel girder BRS energy plate partial self-centering connection by using pre-pull button-through bolts through experiments, and the results showed that BRS energy plate partial self-centering connection had good rotation ability, energy dissipation performance, self-centering efficiency and collapse resistance. Shi Sanyuan and Wang Shuai et al. studied the seismic performance of self-centering girder webs energy-dissipating steel frame joints. Zhou Xingyu and Li Qicai et al. used the Open-sees finite element software to conduct time-history analysis on 27 specimens in 3 groups of a three-story self-centering structure, and studied the influence of self-centering rate on the seismic performance of the structure. Fang Youzhen and Zhao Kai et al. used the finite element software ABAQUS to establish 8 intermediate joint model specimens for the new PEC column-to-steel beam friction energy-dissipation partial self-centering joints and carried out numerical simulation of their mechanical performance under cyclic load. The seismic performance of a new type of friction energy dissipated T-shaped connector with partial self-centering connection for PEC column is also studied.

3. Conclusion
In recent years, the research and development show that the self-centering structure has shown certain advantages in the seismic design of building structures. The engineering application and practice are more and more, and the self-centering components and types are more and more complex and diverse. The self-centering structural system makes full use of the opening performance of the open joints at the contact surfaces, and concentrates the damage on the replaceable energy dissipation elements without damaging the structural members. Post-tensioned prestressing tendons passing through the open joints provide stiffness after contact surface opening and self-centering capability. Energy dissipating devices dissipate seismic energy and are easy to replace. However, the current research on some self-reduction structures is still in the preliminary stage, and the following questions are worthy of further study.

(1) In order to ensure the opening performance of the open joints at the contact surface, further fine
research on the open joints is needed;

(2) In the design of components, the influence of the higher order modes of the structure should be considered;

(3) In order to ensure sufficient safety and reliability of the structure, collapse safety assessment of the self-centering structural system is also an important research direction;

(4) Although the initial cost of the self-centering structural system is higher than that of the traditional structural system, the total life cost of the self-centering structural system should be lower than that of the traditional structural system. Therefore, the quantitative study of the total life cost of the self-centering structural system is also an urgent problem to be solved.

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