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# Quantitative Research on Performance Indicators of Outer Shell Joint Steel Frame

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**ABSTRACT:** Performance-based seismic design method enables structures to achieve different performance levels under different intended use target requirements. In order to coordinate with the three-level fortification goal of Chinese seismic design, this paper analyzed the relationship between the deformation and damage of the structure and components, divided the performance levels of the outer shell joint steel frame into three levels on the basis of domestic and foreign specifications, i.e. good use, life safety and collapse prevention. The inter-story displacement angle was selected as the seismic performance index, the damage degree of the structure and components under three performance levels was comprehensively described, and the recommended values of inter-story displacement angle corresponding to different performance levels were put forward. Meanwhile, combined with the calculation model of the joint deformation, the rotation angle calculation formula of the outer shell joint was proposed. Finally, the rationality of the mechanical model and quantitative performance indicators was verified by experiments.

**KEYWORDS:** Steel frame, Outer shell joint, Quantitative performance index, Interlayer displacement angle.

## I. INTRODUCTION

At present, the seismic design concept of classification is mostly adopted in the seismic codes of various countries, such as the three-level seismic fortification idea of unbreakable in small earthquakes, repairable in moderate earthquakes and uncollapsing in severe earthquakes. The design method based on bearing capacity can avoid structural collapse in large earthquake to ensure life safety. With the development of the city, many buildings with expensive facilities or high investment cause less casualties under the action of the earthquake, however, due to the serious damage of the structure, it has caused great economic losses, which often exceed the expected value of the society and the owner. Therefore, the design method based on the single fortification standard of ensuring life safety is not comprehensive.

In the early 1990s, researchers in the United States and Japan put forward the performance-based seismic design (PBSD) method, that is, the structure can achieve different performance levels under different intended use targets, which can not only effectively control the damage state of the building, but also quantitatively design the deformation requirements of the structure or components, so as to minimize the overall cost of the building. Steel frames with outer shell joints belong to the category of semi-rigid frames, which have been widely used in multi-storey residential buildings because of their good seismic performance and fast construction speed. At present, there are few research results on performance-based indicators of semi-rigid frames, so it is of great significance to carry out quantitative research on PBSD of steel frames with outer shell joints, especially for the application of steel frames in schools and residential systems in high intensity areas.

Paper is organized as follows. Section II describes the application of PBSD in steel structures. In Section III, the division of the performance level and the quantitative value of the performance index of the steel frame with outer shell joints are given, and the expression of the inter-story displacement angle under different performance levels is derived. In Section IV, the reliability of the recommended values of inter-story displacement angle is verified by the test results of outer shell joints. Finally, Section V presents conclusion.

## II. RELATED WORK

The core idea of PBSD is to make the performance of structures under different levels of earthquakes reach the expected performance targets, and to meet the personalized requirements of structures through multi-objective and

multi-level seismic design. PBSD concepts for seismic repair of existing buildings and the design of new buildings have been covered by many guidelines such as FEMA356 [1], ASCE/SEI 41 [2] and FEMA273 [3].

Fragiadakis et al. [4] carried out performance-based multi-objective design of steel structures, taking into account the life cycle cost. Gholizadeh et al. [5] also reported PBSD optimization of steel bending moment frames using a variety of different meta-heuristic optimizers. However, using meta-heuristic optimizers for PBSD of buildings is very expensive. Later, Mansouri S F and Maherim R [6] put forward the optimization technology of constrained control method (CCM), which required much less analysis times than meta-heuristic algorithm and had been developed and applied to PBSD of steel frames. A new braced steel structure strongback system (SBS) proposed by Faramarzi M S and Taghikhany T [7], where PBSD is used as a solution called yield spectrum yield frequency spectra (YFS). In order to properly evaluate the seismic performance of various strongback system (SBS) practical configurations, a series of different SBS prototypes were designed using a direct performance-based approach and the achievement of performance goals was probabilistically evaluated [8].

Since damage can be directly related to displacement, it seems logical to consider displacement in seismic design. In [9], a simple formula was proposed to estimate the peak interlayer displacement modes of eccentrically braced frames (EBF) with different performance levels under seismic ground motion. Shakeri K and Dadkhah H [10] compared direct displacement-based design (DDBD) with performance-based plastic design (PBPD) to determine a more effective design method for steel bending resistant frames. In the above research, the performance-based seismic design of the structure should determine the appropriate seismic performance target according to the characteristics and functional requirements of the structure. In order to apply performance-based seismic design theory to structures, the performance index should be quantified. Therefore, it is necessary to put forward the quantitative index of the performance level of steel frame with outer shell joints.

The work in this study is divided in two stages. 1) Divide performance levels, quantify performance indicators, and 2) verification of test data. According to the Chinese seismic code [11] and FEMA356, the performance levels of steel frame structures are divided into three categories, the limits of inter-storey displacement angles of outer shell steel frames under three performance levels are quantified. Thereafter, the calculation model of the deformation capacity of the outer shell joint is established, and the expressions of the inter-story displacement angles under different performance levels are deduced. Finally, the reliability of the inter-story displacement angle under each performance level is verified by test data.

### III. METHODOLOGY

The seismic fortification level is mostly based on the fortification target of the structure, and many countries adopt the multi-stage fortification target, so the seismic fortification level is also multi-stage. The Chinese seismic code [11] divides the seismic fortification standards into three levels, i.e. small earthquakes, moderate earthquakes and major earthquakes, and FEMA356 [1] defines the seismic risk level as four levels.

The structural performance level is the maximum allowable damage specified for the designed building under the earthquake action that may be encountered. The damage degree of the overall structure, structural members, non-structural members and other factors of the building shall be specified. There are many ways to describe the performance level of the structure, which needs to reflect whether and how much the function is affected. There are different classifications of structural performance levels at home and abroad. The structural performance level is divided into five grades in Classification of earthquake damage to buildings and special structures [12], as shown in Table 1.

Table 1. Classification of earthquake damage grade of buildings

Destruction level	Destruction description	Possibility of continued use
Basically intact	Load-bearing members are intact, individual non-load-bearing members are slightly damaged, auxiliary components are damaged to varying degrees.	Generally, it can be used continuously without repair.
Minor damage	Individual load-bearing members have slight cracks, individual non-load-bearing members are	Do not need to repair or slightly repair, can still



	obviously damaged, and ancillary components are damaged to varying degrees.	continue to use.
Moderate damage	Most of the load-bearing members have slight cracks, some of them have obvious cracks, and some non-load-bearing members have been seriously damaged.	General repair is required, and it can be used properly after taking safety measures.
Serious damage	Most load-bearing members are seriously damaged or partially collapsed.	Should be overhauled and partially dismantled.
Collapse	Most load-bearing members collapse	Need to be dismantled.

The FEMA356 comprehensively considers the damage levels of structures and components, and divides the performance levels of structures into four levels, i.e. OP, IO, LS and CP, which are normal use, immediate occupancy, life safety, and collapse control, as shown in Figure 1. Among them, the OP state corresponds to the intact structure, the IO state corresponds to the structure that may be damaged, but the basic functions are not affected, the LS state corresponds to the main structure with severe damage but does not affect the load-bearing, and the CP state corresponds to the main structure with serious damage, but it will not collapse.

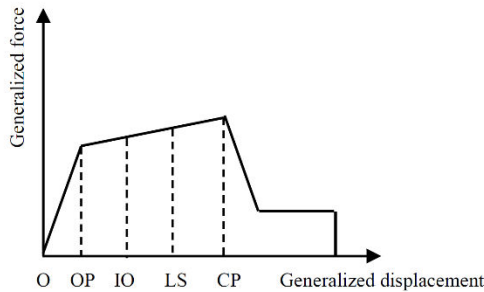


Fig. 1. Generalized force-deformation curves in FEMA356

The performance indicators defined by FEMA356 are transformed into structural performance indicators that conform to the three-level seismic fortification in the Chinese seismic code, namely the small earthquake index, the medium earthquake index and the major earthquake index, as shown in Table 2.

Table 2. Comparison of performance indexes between Chinese seismic code and FEMA356

Component state	FEMA356 index	Chinese seismic level
Elasticity	OP	
Close to yield	IO	Small earthquake stage
Yield not collapsed	LS	Medium earthquake stage
Close to collapse	CP	Major earthquake stage

Table 3. Classification of earthquake damage grade of buildings

Performance level	Destruction level	Damage of steel frame structure			
		Structure	Structural member	Non-structural components	Personnel safety and continued use
Good use	Slight damage	The structure is basically intact and the main functions are not affected.	1) Slight local yield occurred in a few sites 2) Minor buckling or observable permanent deformation occurs in the member.	Individual components are damaged.	It can continue to be used without repair or slight repair, and the personnel are safe.
Life safety	Moderate damage	The structure may be damaged and	1) Plastic hinges are formed, some beams are partially	Serious damage to some	It can continue to be used after general repair



		the main functions can be repaired.	<ol style="list-style-type: none"> <li>2) buckled</li> <li>Severe joint deformations</li> <li>3) Individual moment connections are damaged, but shear connections remain intact</li> <li>4) A few members may have local fractures.</li> </ol>	components.	and will not be life-threatening.
Prevent collapse	Serious damage	The structure is seriously damaged, but it does not affect the load-bearing, and the local function is lost.	<ol style="list-style-type: none"> <li>1) The beam-column joint area is severely deformed, and the moment connection is damaged in many places</li> <li>2) The shear connection remains intact.</li> </ol>	Most components are damaged and may fall, but no injuries.	It should be overhauled and partially demolished, and life safety is still guaranteed.

With reference to the above-mentioned domestic and foreign structural performance classification standards, the performance levels of steel frame structures are divided into three levels, i.e. good use, life safety, and collapse prevention. The comprehensive description of the structural damage corresponding to the three performance levels is shown in Table 3. The three levels can comprehensively reflect the failure performance of the structure under the action of earthquake.

According to the performance levels of the structural members defined in Table 3, the damage of the outer shell joints under the three performance levels of good use, life safety, and collapse prevention are respectively described qualitatively, as shown in Table 4.

Table 4. Performance level of outer shell joints

Performance level	Component status	Qualitative description
Good use	Approximate elasticity	The tension T-stub has a gap with the column wall, the beam flange has a slight local yield, and the joint area has a local plastic deformation.
Life safety	Plastic development	The flange of the beam yielded, local buckling occurred, and plastic hinge is initially formed.
Prevent collapse	Destruction	The beam ends form obvious plastic hinges, and the joint area is severely deformed.

To sum up, from a macro point of view, the description of the damage of structures and components can only be used to investigate whether the structure meets the requirements of the expected design performance level after the earthquake, however, the performance level must be quantified to guide seismic design. Therefore, the rational quantitative description of earthquake damage level is very important.

**Recommended value of performance index of outer shell joint steel frame**

In performance-based design theory, the performance index of a structure or component can be defined by one or several parameters, such as stress, displacement, energy dissipation, etc. Although the division of structural performance by a certain parameter may not be perfect, it is simple and practical to divide the level of structural performance based on displacement (deformation). As the interlayer displacement angle has a good correlation with the damage degree of the structure in each stage, it can better reflect the performance of the structure under earthquake action than strength. According to the current domestic and foreign codes and related research results, the deformation limits of structures with different performance levels are proposed.

(1) Deformation limit of good use level

When the performance level is good use, structural members and non-structural members may be slightly damaged, but the overall structure is intact and the function is not affected. The failure state corresponds to the small earthquake

stage specified in the seismic code [11]. Therefore, the limit value of the inter-story elastic displacement angle under small earthquakes can be selected as the deformation limit value corresponding to this level, that is, 1/250.

(2) Deformation limit of life safety level

The structure corresponding to this level may be damaged after the earthquake, but it can still be used after general repair or without repair. This state of moderate damage is basically the same as that of moderate earthquake repairable. A large number of research results of Pushover analysis and elastoplastic time-history analysis of steel frame-braced structures are summarized [13], when the maximum inter-story displacement angle of the structure is in the range of 1/200 - 1/152, the failure of members accords with the macroscopic description of moderate failure performance level. Considering that the lateral stiffness of frame structure is smaller than that of frame-braced structure, and the outer shell joint steel frame belongs to semi-rigid frame. It is suggested that when the performance level is life safety, the corresponding deformation limit should be 1/150.

(3) Deformation limit of collapse prevention level.

The structure corresponding to this performance level is severely damaged but does not affect the load-bearing, the life safety can still be guaranteed, but the partial function of the structure may be lost. This state of severe damage is consistent with the stage of major earthquake. Therefore, the deformation limit value corresponding to the performance level can be taken as 1/50 by referring to the limit value of the elastic-plastic interlayer displacement angle under the action of major earthquakes in the seismic code[11].

In accordance with three levels in Chinese seismic design code, the limit values of inter-storey displacement angles of outer shell joint steel frame under different performance levels are given. Corresponding to performance levels of good use, life safety and collapse prevention, the recommend displacement angle limit values are 1/250, 1/150 and 1/50 respectively.

**Theoretical analysis of deformation capacity of outer shell joint**

Due to the difference of joint size, geometric characteristics and mechanical performance, the deformation capacity of structure or member is different, moreover, the cost of experimental research is high. Hence it is necessary to establish a calculation model of joint deformation ability, the inter-story displacement angle of steel frame structure can be preliminarily judged theoretically.

The middle joint of the middle column of a typical pure steel frame structure is selected as the research object, and the joint rotation angle is the inter-storey displacement angle of the frame. Figure 2 shows the composition of the inter-storey displacement angle of steel frame. It can be seen that the inter-storey displacement angle is composed of the  $\theta_{cy}$  caused by the relative lateral displacement of the column top, the bending rotation angle  $\theta_{by}$  at the beam end, the rotation angle  $\theta_s$  caused by the shear deformation of the beam-column and  $\theta_{jy}$  caused by the shear deformation of the joint[14].

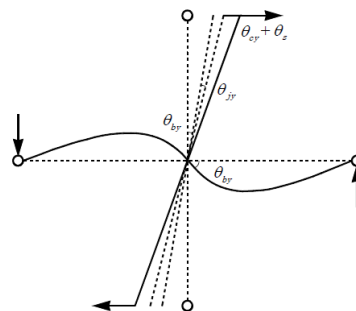


Fig. 2. The composition of the interlayer displacement angle.

For steel frame structures, the span of the beam is generally greater than the height of the column, and the curvature of the beam is greater than that of the column. Therefore, the bending deformation of the beam is an important part of the interlayer deformation. The effective yield curvature of the beam is  $\varphi_{by} = 2.2\varepsilon_y/h_b$ . The yield displacement angle value  $\theta_{by}$  produced by the bending deformation of the frame beam is shown in Equation 1.

$$\theta_{by} = \frac{1}{6} \varphi_{by} L = \frac{1}{6} \times \frac{2.2\varepsilon_y}{h_b} \times L = 0.37\varepsilon_y \left( \frac{L}{h_b} \right) \tag{1}$$



Where  $\varphi_{by}$  is the yield curvature of the H-section steel beam,  $\varepsilon_y$  is the yield strain of the steel,  $h_b$  is the section height of the section steel beam, and  $L$  is the span of the beam.

For the joints with failure at the beam end, the rotation angle caused by column lateral displacement during specimen yield accounted for about 40% of the beam end angle. With the progress of loading, the displacement proportion of beam end caused by beam deformation gradually increased. It is assumed that the height of a typical steel frame structure is 3m and the span is 6m. Based on the actual structure,  $\theta_{cy}$  caused by column lateral displacement is about  $0.4\theta_{by}$ ,  $\theta_{jy}$  caused by joint shear deformation accounts for 25% of  $\theta_{by}$ , and  $\theta_s$  generated by beam-column shear deformation accounts for 10% of  $\theta_{by}$ , then the interlayer yield displacement angle of steel frame  $\theta_y$  is

$$\theta_y = \theta_{by}(1 + 0.4 + 0.25 + 0.1) = 0.64\varepsilon_y \left(\frac{L}{h_b}\right) \tag{2}$$

For the full-scale joint specimen in the test [15],  $\theta_y$  can be calculated according to the above theoretical formula

$$\theta_y = 0.64\varepsilon_y \left(\frac{L}{h_b}\right) = \frac{1}{38} \tag{3}$$

In the above theoretical derivation process, the yield state of the structure is defined as the beam flange section fully entering yield. It can be seen that the yield state corresponds to the life safety performance level of the steel frame structure. The inter-story displacement angles of steel frame structures at different performance levels are limited to 1/250, 1/150, and 1/50 respectively. Using the method of numerical interpolation and probability guarantee, the expression of the inter-story displacement angles of the outer shell steel frame under the two performance levels of good use and collapse prevention are obtained, which are denoted by  $\theta_e$  and  $\theta_u$  respectively.

$$\theta_e = 0.26\varepsilon_y \left(\frac{L}{h_b}\right) = \frac{1}{94} \tag{4}$$

$$\theta_u = 1.06\varepsilon_y \left(\frac{L}{h_b}\right) = \frac{1}{23} \tag{5}$$

#### IV. EXPERIMENTAL RESULTS

Typical cross-shaped joints was selected for the outer shell joint tests [15], the rotation angle of the joint is the interlayer displacement angle of the frame. Based on the test results, the rotation angles of the specimens at the performance level of good use, life safety and anti-collapse are shown in Table 5.

Table 5. Rotation angle of outer shell joints under different performance levels

Specimen	Rotation angle at different performance levels (rad)					
	Good use		Life safety		Prevent collapse	
	Positive Loading	Negative Loading	Positive Loading	Negative Loading	Positive Loading	Negative Loading
STj-A	0.016	0.016	0.035	0.039	0.68	0.081
STj-B	0.014	0.011	0.03	0.026	0.048	0.043

The joint rotation angle is used to control the performance level of the elastic-plastic state of the specimen, which reflects the degree of plastic development of the outer shell joint to a certain extent. According to the test data, the distribution range of joint rotation angle is 1/91~1/63 at good use performance level. At life safety performance level, the distribution range of joint angle is 1/38~1/26. At collapse prevention performance level, the distribution range of joint angle is 1/23~1/12.

Table 6. Inter-story displacement angle of steel frame with outer shell joints

Inter-story displacement angle	Performance Level		
	Good use	Life safety	Prevent collapse
Test value	1/91~1/63	1/38~1/26	1/23~1/12
Theoretical value	1/94	1/38	1/23
Suggested value	1/250	1/150	1/50

As shown in Table 6, compared with the suggested values and theoretical calculation values of inter-story displacement angle of steel frame, the outer shell joints have good ductility and strong plastic deformation ability. The theoretical calculation method can accurately calculate the inter-story displacement angle of the structure under



different performance levels, meanwhile, it also reflects that the recommended values of the inter-story displacement angle of the outer shell joint steel frame are safe, which can be used to guide the performance-based design of the structure.

## V. CONCLUSION

Reasonable performance objectives are the premise of structural performance-based seismic design. In order to refine the seismic concept of multi-level fortification of steel frame structures, this paper conducted quantitative research on the performance indicators of steel frames with outer shell joints, and the following conclusions were obtained.

(1) Referring to Chinese seismic code and the classification standard of structural performance level in FEMA356, the performance level of steel frame structure is divided into three levels, i.e. good use, life safety and collapse prevention. The recommended values of story drift angle of steel frame structure with outer shell joints under three performance levels are 1/250, 1/150 and 1/50 respectively.

(2) The calculation model of the deformation capacity of the outer shell joints is established to preliminarily judge the inter-story displacement angle of the steel frame under different performance levels.

(3) According to the test results of the outer shell joints, it is reflected that the joints have good ductility and strong plastic deformation ability, which verifies the rationality of the theoretical model and quantitative performance indicators.

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