PERFORMANCE BASED SEISMIC DESIGN OF HINGED WALL WITH BRBS IN BASE BASED ON EQUAL DISPLACEMENT PRINCIPLE

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Abstract

Hinged Wall with BRBs in Base (HWBB) consisting of a hinged wall with two BRBs installed symmetrically on both sides at the bottom of the hinged wall and gapped tendons is able to control the deformation mode of the frame structure and avoid soft story failure during earthquakes. The frame in this paper is hinged frame which carries only vertical load and lateral load is only carried by HWBB. The hinged wall remains elastic while BRBs dissipate all the seismic energy. Gapped tendons provide the third stiffness for the structure to resist collapse due to P-Δ effect as the post-elastic stiffness of BRB is small. HWBB belongs to resilient structures as the function of the structure can be repaired after an earthquake by replacing BRBs and gapped tendons. Previous numerical analysis and experiments have shown the excellent performance of HWBB.

In this paper, the performance based seismic design method of HWBB-hinged frame structure is proposed. BRBs and the gapped tendons provide the flexural resistance and the hinge point resist all the lateral load and vertical load. First, the equal displacement principle is verified by considering the P-Δ effect. The design method belongs to direct displacement based design method. Design objectives are gotten from the Chinese seismic code for performance based design and the controlled seismic level of each performance objective is figured out by the equal displacement principle. The deformation of HWBB-hinged frame structure is controlled by the first mode and not sensitive to higher mode effects, which are analyzed through the distributed parameter models of HWBB-hinged frame. The HWBB-frame structure is simplified to a SDOF system based on the first mode. The stiffness demand is gotten from the elastic displacement spectrum. Higher mode effects have to be considered when design the strength of the elastic hinged wall as the inner forces in the wall are largely affected by higher mode effect. The design flowchart is given, including the derivation of the equivalent lateral stiffness of the structure. Design parameters include the length of the wall, the area of the core of BRB and the length of BRB. Nonlinear time history analysis (NTHA) is conducted to validate the design method. Based on the NTHA of an example HWBB designed according to the proposed design method, the design objectives are met, including the objective of the controlled seismic level and those of the other two seismic levels. Design parameters of the gapped tendons include the area of the tendon, the initial gap and the length of the tendon. Parametric study is conducted to provide optimal ranges for the design of the gapped tendon. The design method provides a basis for the application of this structure to practical projects.

Keywords: Hinged wall with BRBs in base; gapped tendon; equal displacement principle; performance based seismic design; seismic design procedure

1. Introduction

Rocking wall is able to control the deformation pattern of the frame structure. Rocking walls are composed of both the traditional stepping rocking wall which rotates around the two sides at the bottom of the wall and hinged wall which pivots about the middle point at the bottom of the wall. However, the energy dissipating capacity of rocking wall is small. Therefore, energy dissipaters are installed in rocking walls to increase the energy dissipation ability.

Design methods for rocking walls have been proposed by many researchers and most of the design methods belong to performance based design methods. Direct displacement based design approach, which is proposed by Priestley *et al.* [1], is the most popular performance based design method. Most of the research is on stepping rocking wall. For example, Nicknam and Filiatrault [2] developed a direct displacement-based design method for Propped Rocking Wall systems where BRBs were used as the energy dissipating devices. Marriott [3] proposed a direct displacement based design method for the precast post-tensioned walls installed with viscous fluid dampers and tension-compression yielding steel dampers. Toranzo et al. [4] proposed a displacement based design method for rocking confined-masonry walls with hysteretic energy dissipaters fixed at the base. Other researchers also proposed performance based design methods for rocking walls. Kurama *et al.* [5] proposed a performance based design method for unbounded post-tensioned precast concrete walls. Smith *et al.* [6] presented the seismic design procedure for the hybrid shear wall system installed with mild reinforcing steel. Perez *et al.* [7] presented the seismic design approach of precast concrete wall panels connected along vertical joints with ductile connectors. Performance based design methods for hinged walls were also proposed by many researchers. Takeuchi and Suzuki [8] and Chen *et al.* [9] proposed a design method based on the equivalent linearization techniques for a spine frame system installed with Buckling Restrained Columns. Qu [10] proposed a design method which is a combination of force based design method and performance based evaluation method for a rocking wall-frame structure where steel dampers were installed between the hinged rocking wall and the steel reinforced frame [11]. Grigorian and Grigorian [12, 13] proposed formulations for the design of the rocking-wall moment frame systems. Design methods discussed above use the equivalent linear method, i.e. linear displacement spectrum reduced by damping. However, the equivalent linear method can underestimate the displacement and ductility demand [14]. Therefore, Chopra and Goel [14] proposed the inelastic displacement spectrum method.

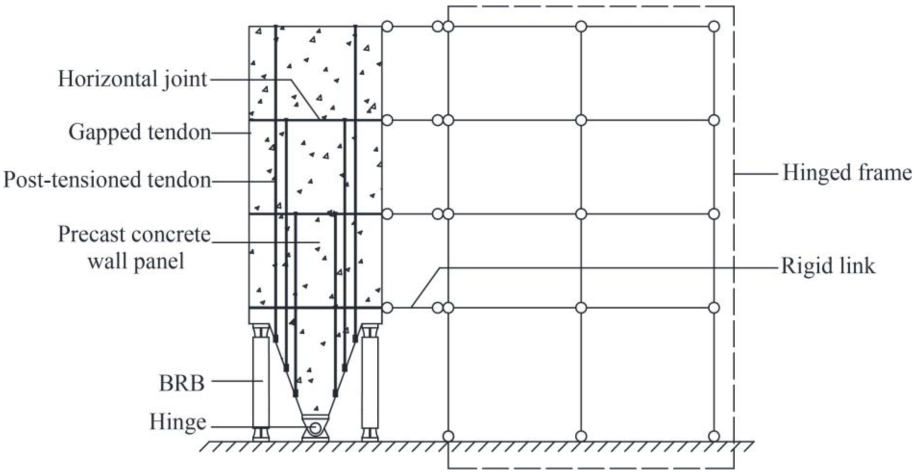

Fig. 1 – HWBB-hinged frame structure

In this paper, a performance based design method for Hinged Wall with BRBs in Base (HWBB) is proposed. As shown in Fig.1, HWBB is composed of a hinged wall and two BRBs installed symmetrically on both sides at the bottom of the wall. The hinged wall is composed of precast concrete wall panels connected by post-tensioned tendons. The joints in the hinged frame including both beam to column and column to foundation are hinged connections, which can be seen from the dashed box. Therefore, the lateral stiffness of the hinged frame is zero. HWBB and the hinged frame are connected by diaphragm, which can be simplified as rigid links due to its large in-plane stiffness. HWBB is able to control the deformation pattern of the hinged frame, avoiding weak story failure. HWBB-hinged frame structure has separate load bearing mechanism. HWBB bears all the lateral load and the hinged frame bears all the vertical load. As the post-yielding stiffness of the HWBB-hinged frame is small compared to the elastic stiffness after BRBs yield, gapped tendons are added to provide the third stiffness and avoid collapsing due to P-Δ effect. The design method in this paper is based on the elastic displacement spectrum using equal displacement principle, which will be verified in section 2. A flowchart of this design method is given. Besides, an example is designed based on this method to verify whether the design objectives are met.

2. The verification of the equal displacement principle.

According to Chopra [15], the equal displacement principle applies to the SDOF system with natural periods larger than about 0.7s. Structures with elastic perfect plastic hysteresis rule and period larger than 0.7s conforms to the equal displacement principle [1]. The hysteretic rule of the HWBB-hinged frame is elastic perfect plastic and the period of this type of structure is larger than 0.7s. To investigate whether the equal displacement principle is met by this type of structure when considering the P-Δ effect, an example is studied through Nonlinear Time History Analysis (NTHA). Fig.2 illustrates the layout of the example structure. The structure is a 12-story HWBB-hinged frame structure with story height as 4m. Design intensity is 7 [16]. The site is the third type and belongs to the second group. The representative value of gravity load of each story is 11600kN. The area of the core plate of BRB is 22000mm^2 and Q235 is used as the core plate whose yielding strength is 200MPa. The fundamental period of this structure is 3.22s.

Ground motions are chosen from the Far-Field Set in FEMA P695 [17] and the 22 ground motions [10]. Information of the ground motions are shown in Table 1. Fig.3 shows the design spectrum, the response spectrum of each ground motion and the mean response spectrum when the PGA is scaled to 35cm/s^2. The spectral value corresponding to the fundamental period is larger than the mean spectral value at the fundamental period.

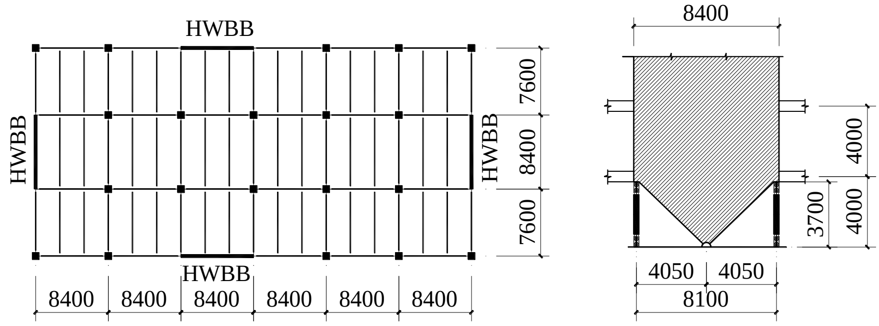

Fig. 2 – The layout of the structure

NTHA is performed under three seismic levels, i.e., Frequent Earthquakes (FE), Local Fortification Intensity Earthquake (LFIE) and Rare Earthquake (RE). P-Δ effect is considered during the analysis. As shown in Fig.4, the average value of the top displacement under three ground motion levels varies almost linearly with the PGA, revealing that the equal displacement principle is met.

Table 1 – Information of the selected ground motions

ID	M	Year	Name	Recording station name
1	6.5	1976	Friuli, Italy-01	Tolmezzo
2	6.93	1989	Loma Prieta	Gilroy Array #3
3	6.69	1994	Northridge-01	Castaic
4	6.69	1994	Northridge-01	Santa Monica
5	7.14	1999	Duzce, Turkey	Bolu
6	8.00	2008	Wenchuan, China	Jiangyou
7	6.7	1994	Northridge	Beverly Hills-Mulhol
8	6.7	1994	Northridge	Canyon Country-WLC
9	7.1	1999	Duzce, Tuekey	Bolu
10	6.5	1979	Imperial Valley	El Centro Array #11
11	6.9	1995	Kobe, Japan	Nishi-Akashi
12	6.9	1995	Kobe, Japan	Shin-Osaka
13	7.5	1999	Kocaeli, Tuekey	Arcelik
14	6.9	1989	Loma Prieta	Capitola
15	6.9	1989	Loma Prieta	Gilroy Array #3
16	7.4	1990	Manjil, Iran	Abbar
17	7.6	1999	Chi-Chi, Taiwan	TCU045
18	6.6	1971	San Fernando	LA-Hollywood Stor
19	6.5	1976	Friuli, Italy	Tolmezzo

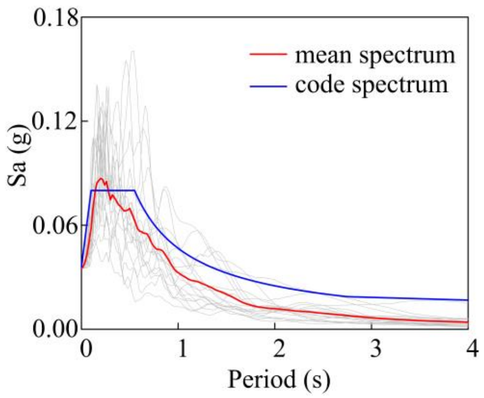

Fig. 3 – The design spectrum and response spectrum of ground motions

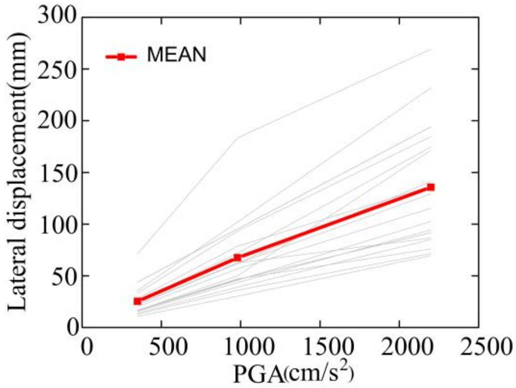

Fig. 4 – The maximum top displacements under three ground motion levels

3. Design method

3.1 Performance objective

Performance objectives are defined based on the Chinese seismic code [16]. A performance objective refers to performance levels corresponding to different ground motion levels. Three ground motion levels are FE, LFIE, and RE with return periods as 50, 475 and 2745 years, respectively. Performance levels are defined in terms of the maximum inter-story displacement, which is related to the maximum inter-story drift ratio. There are four performance objectives as shown in Table 2. δ_e is the limit for elastic displacement; δ_p is the limit for plastic displacement.

Table 2 – Inter-story displacement requirement for four performance objectives

Performance level	**Frequent earthquake**	**Moderate earthquake**	**Rare earthquake**
Performance 1	Well, the deformation is far smaller than δ_e	Well, the deformation is smaller than δ_e	Almost well, the deformation is slightly larger than δ_e
Performance 2	Well, the deformation is far smaller than δ_e	Almost well, the deformation is slightly larger than δ_e	There is slight plastic deformations, the deformation is smaller than $2\delta_e$
Performance 3	Well, the deformation is obviously smaller than δ_e	Slight damage, the deformation is smaller than $2\delta_e$	There is obvious plastic deformations, the deformation is about $4\delta_e$
Performance 4	Well, the deformation is smaller than δ_e	Slight~moderate damage, the deformation is smaller than $3\delta_e$	Not serious damage, the deformation is not larger than $0.9\delta_p$

After choosing a performance objective, the limit for the maximum inter-story drift ratio corresponding to three ground motion levels can be determined from Table 2. Based on the equal displacement principle and the fact that the deformation shape of the HWBB-hinged frame is nearly linearly distributed along the height of the building, the controlled ground motion level of each performance objective for design precautionary intensities lower than 8 (intensity 6, 7 and 7.5) is figured out in Table 3 based on the ratio of Peak Ground Acceleration (PGA) corresponding to three ground motion levels.

Table 3 – Controlled ground motion level for different performance levels for intensity lower than 8

Seismic level	Performance 1	Performance 2	Performance 3	Performance 4
Frequent earthquake				✓
Moderate earthquake				
Rare earthquake	✓	✓	✓	

3.2 Design procedure

Firstly, the HWBB is designed by a displacement based design method. Then, the third stiffness conponent is designed.

3.2.1 Deisgn of HWBB

Two BRBs which provide the moment resistance can be simplified as a rotational spring with rotational stiffness as k_b, as illustrated in Fig.5.

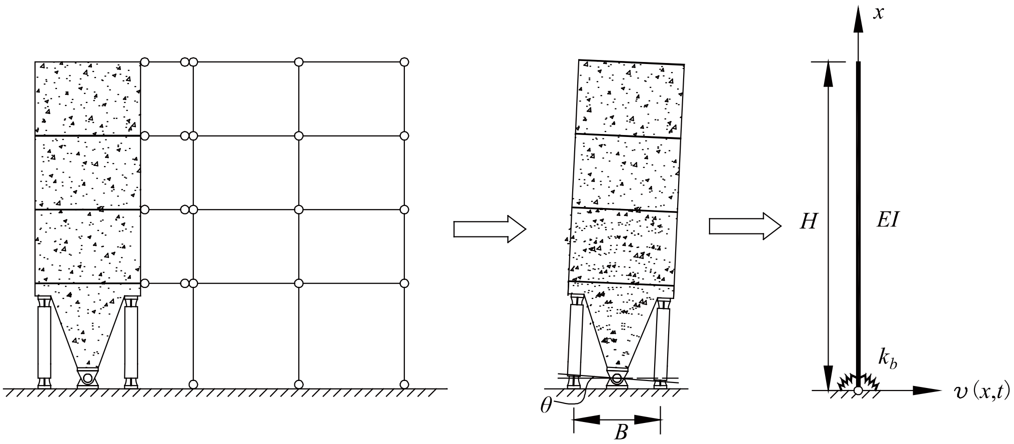

Fig. 5 – Simplified model of the HWBB-hinged frame structure

The moment resistance offered by the rotational spring in the simplified model is expressed as

$$M = k_b \theta \tag{1}$$

where θ denotes the inter-story drift ratio of the first story, which is caused by the rotation of the hinged wall and is calculated by the deformation of BRB as follows:

$$\theta = \frac{\Delta u_{BRB}}{0.5B} = \frac{2\varepsilon_{BRB} l_{BRB}}{B} \tag{2}$$

where ε_{BRB} denotes the strain in BRB ; l_{BRB} is the length of BRB; Δu_{BRB} is the deformation of BRB; and B is the distance between centerlines of BRBs. Substituting Eq. (2) into Eq. (1) gives

$$k_b = \frac{M}{\theta} = f_{BRB} AB \cdot \frac{B}{2\varepsilon_{BRB} l_{BRB}} = \frac{EAB^2}{2l_{BRB}} \quad (3)$$

where A denotes the area of the core plate in BRB and E is the elastic modulus of steel.

The HWBB can be simplified as an Equivalent Single Degree Of Freedom (ESDOF) system which consists of a SDOF system with a rotational spring at the bottom, as illustrated in Fig.6. As HWBB can control the deformation pattern of the frame, HWBB-frame is simplified as a SDOF system based on the first mode. The influence of higher mode effect on HWBB-hinged frame is investigated by a distributed parameter model and the results demonstrate that the displacement is not sensitive to higher mode effects even after BRBs yield [18]. However, higher mode effects have to be considered when determine the strength demand of the hinged wall. A seismic intensity superposition method was proposed by Yang [19] to calculate the moment demand in the hinged wall. The equivalent mass, the equivalent height and the design displacement are shown in the Eq. (4), Eq. (5) and Eq. (6), respectively [15].

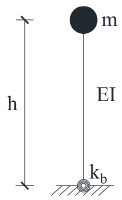

Fig. 6 – The ESDOF model of HWBB-hinged frame

$$M_{eq} = \frac{\left(\sum_{i=1}^{N} m_i \cdot \phi_{i1}\right)^2}{\sum_{i=1}^{N} m_i \cdot \phi_{i1}^2} \quad (4)$$

$$H_{eq} = \frac{\sum_{i=1}^{N} m_i \cdot \delta_i H_i}{\sum_{i=1}^{N} m_i \cdot \delta_i} \quad (5)$$

$$u = \frac{\Delta_{roof}}{\Gamma_1 \Phi_{N1}} \quad (6)$$

Where Δ_{roof} is the top design displacement of the original structure; Φ_{N1} is the top element in the first mode shape vector; H_i is the height of the ith floor from the ground.

The equivalent lateral stiffness of the ESDOF system k_t can be derived by the lateral stiffness of the elastic cantilever wall k_a and the lateral stiffness contributed by the rotational spring k_B, as shown in Eq. (7) and Eq. (8). The ealstic cantilever wall and the rotational spring are in series.

$$\frac{1}{k_t} = \frac{1}{k_a} + \frac{1}{k_B} = \frac{h^3}{3EI} + \frac{h^2}{k_b} \quad (7)$$

$$k_t = \frac{3EIk_b}{h^2\left(hk_b + 3EI\right)} \quad (8)$$

Design flowchart is shown in Fig.7. Design procedures are:

1). Select performance objective and seismic precautionary intensity; then the controlled ground motion level can be determined from Table 3. Therefore, the demand for the maximum inter-story drift ratio is determined. Determine the general layout of the building; choose the length of the wall and the length of BRB based on the layout of the structure.

2). Build the ESDOF system of HWBB, determine the equivalent mass M_{eq}, the equivalent height h_{eq} and the design displacement u corresponding to the first mode.

3). Determine the period T according to the design displacement u using the elastic displacement spectra.

4). Determine the lateral stiffness demand of the HWBB:

$$k_d = M_e \frac{4\pi^2}{T^2} \tag{9}$$

5). Determine the area of the core plate. If the calculated area is smaller than zero, the length of the wall or the number of the wall has to be increased in step 1). Then repeat 1) to 5).

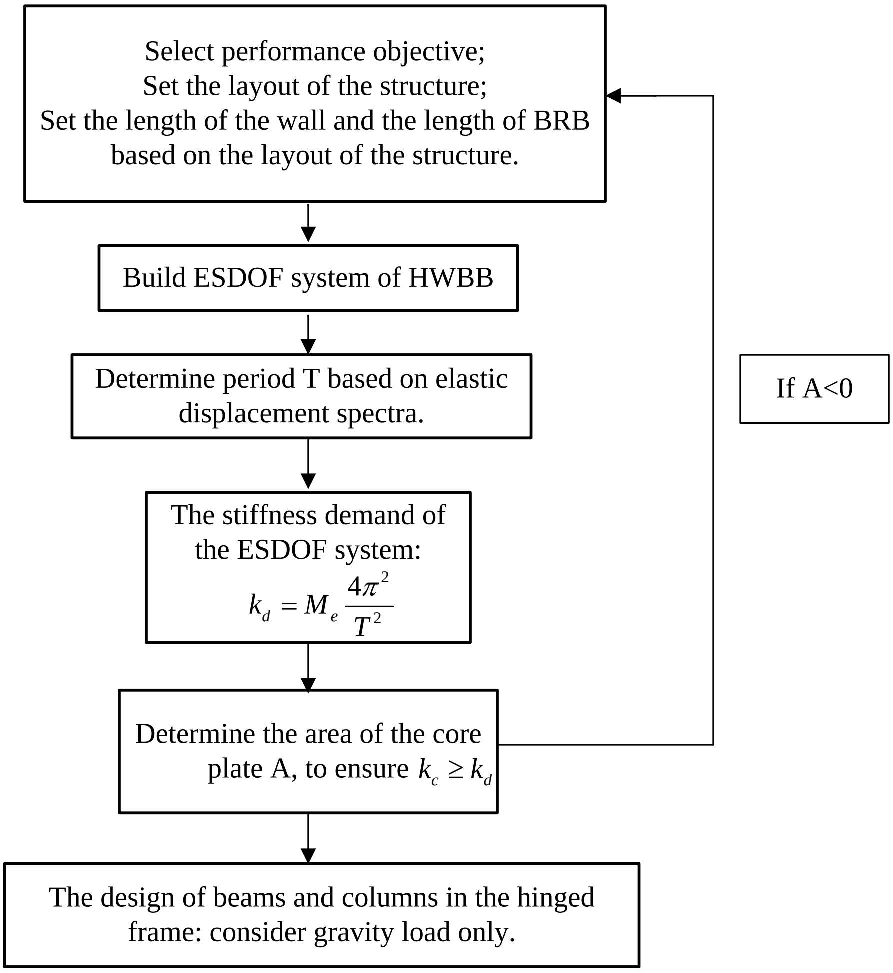

Fig. 7 – Design flowchart

3.2.2 Design of the third stiffness component-gapped tendons.

As shown in Fig.8, gapped tendons are installed symmetrically on both sides along the height of the wall. Due to the small post-yielding stiffness of HWBB, gapped tendons are installed in HWBB to provide the third stiffness for HWBB, avoiding collapsing due to P-Δ effect. Design components of the third stiffness component include the area of the gapped tendon, the magnitude of the initial gap and the length of the gapped tendon.

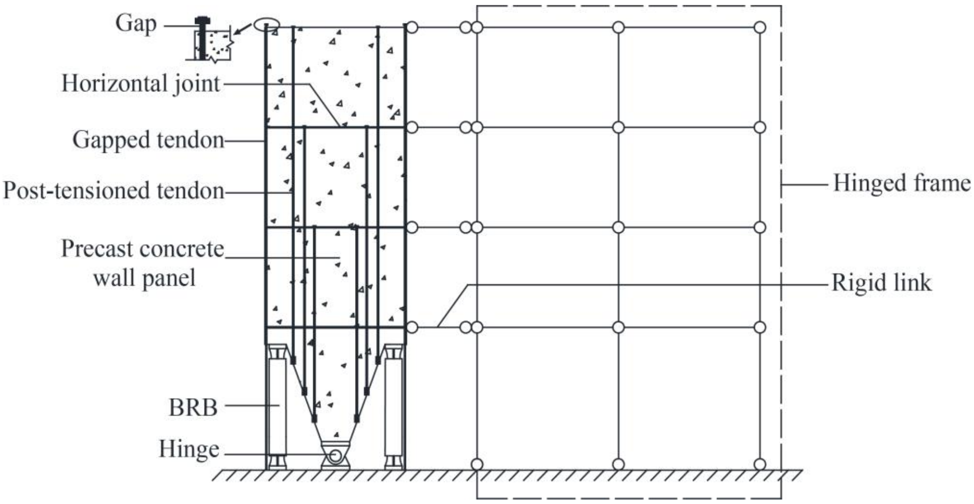

Fig. 8 – HWBB with gapped tendons-hinged frame structure

After BRBs yield, gapped tendons begin to provide the third stiffness. In the global force-displacement curve, the global lateral force declines after the tensioned BRB fractures. The compressed BRB still bears compression. Therefore, the magnitude of the declined lateral force equals to half the horizontal force corresponding to the moment resisted by two BRBs before the tensioned BRB fractures. Assuming the flexural stiffness of the hinged wall is infinite, the global lateral stiffness contributed by the tensioned gapped tendon (under a concentrated top force) is as follows:

$$K_{lateral} = \frac{0.25B^2 A_t E_t}{l^t h^2} \tag{12}$$

Where, A_t is the area of the gapped tendon; l^t is the length of the gapped tendon. Further studies need to be conducted to determine the magnitude of the three parameters in the third stiffness component.

4. Example.

NTHA is conducted on an example model to verify if the design objective is met under three seismic levels. The layout of the example is the same as the structure in section 2. The design objective is performance 3. The controlled seismic level is the rare earthquake. Therefore, the limit for the maximum inter-story drift ratio is 2/275. Due to the symmetry of the structure, a half-strucutre is analyzed.

Design procedures are as follows:

1). Calculate the properties of the ESDOF system: the equivalent mass is 5428.8t, the equivalent height is 33.3m, and the equivalent design displacement is 0.242m.

2). Due to the design displacement, the period is 2.9s.

3). The lateral stiffness demand is: $k_d = 2.546 \times 10^7 kg \cdot s^{-2}$.

4). The area of the core plate of BRB is 40522.5mm^2.

The numerical model is built in OpenSees [20]. The wall is modeled using the elasticBeamColumn element. Truss element is used to model BRB. The hinged frame is modelled using the concentrated mass model. The elasticBeamColumn element is used to model the concentrated columns in each story. ZeroLength element with little rotational stiffness is used between adjacent concentrated columns to model the hinge effect in the hinged frame. Rigid link is used to connect the hinged wall and the hinged frame at each floor. Ground motions are the same as those defined in section 2.

The fudamental period of the example structure is 2.73s. As shown in Fig.9(a)-(c), the mean maximum interstory drift under three seismic levels are within the limits under three seismic levels. Therefore, design objectives are met. In Fig.9(d), the maximum interstory drift varies almost linearly with the PGA, which verifies the equal displacement principle.

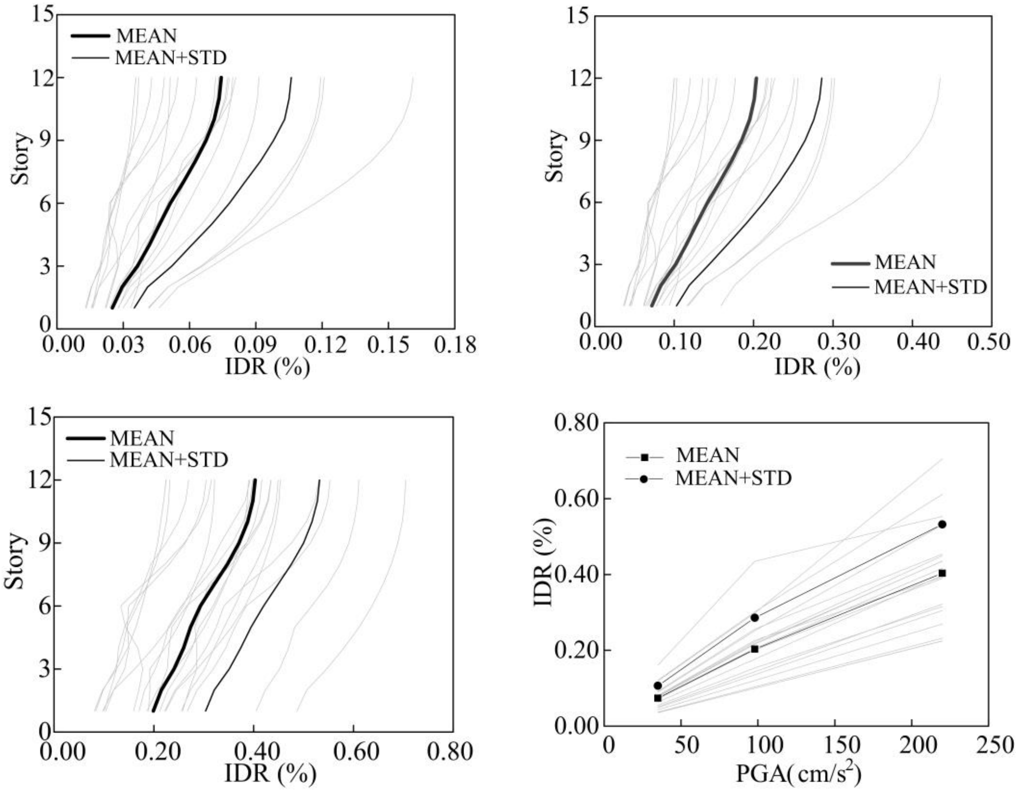

Fig. 9 – The distribution of the maximum inter-story drift ratio (IDR) under (a) Frequent earthquake, (b) Moderate earthquake, (c) Rare earthquake; and (d) IDR vs. PGA

Gapped tendons are added to the example model. Parameters of the gapped tendons are: the elasticity of modulus of the gapped tendon is 2.06E+5MPa; the initial gap is 24mm; the area of the gapped tendon is 3.0E+4mm^2. Truss element is used to model the gapped tendons. The Elastic-Perfectly Plastic Gap Material is used as the constitutive model of the gapped tendons. A pushover analysis is conducted on the example. As shown in Fig.10, the third stiffness was provided after BRBs yields. The structure yielded at 1/6 lateral drift. The gapped tendons began to work at the 0.56 lateral drift and the third stiffness is the red line shown in this figure.

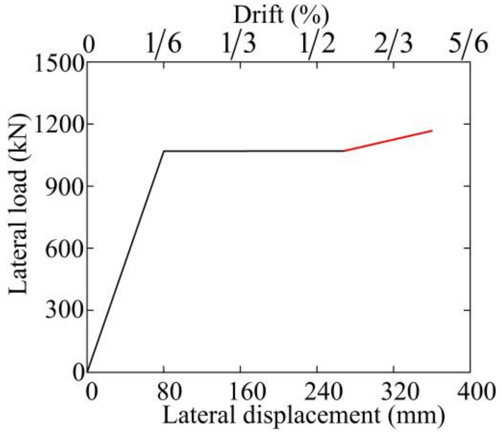

Fig. 10 – Pushover curve of the HWBB installed with gapped tendons structure

5. Conclusion

A performance based design method of HWBB-hinged frame structure is proposed using the equal displacement principle. Design procedures are given. An example structure is designed according to the design method. NTHA results verified the effectiveness of this design method as the design objective was met. Pushover analysis was conducted on the example to demonstrate that the third stiffness began to work when the gap was closed.

6. Acknowledgements

This study was financially support by the National Key Research and Development Program of China (No.2018YFC0705802), the National Natural Science Foundation of China (No.51978165), the Fundamental Research Funds for the Central Universities (No.3205007720), Postgraduate Research and Practice Innovation Program of Jiangsu Province (No.3205007720), and China Scholarship Council for visiting studentship.

7. Copyrights

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