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SEISMIC ASSESSMENT OF AN EXISTING 20-FLOOR CONCRETE SHEAR WALL BUILDING IN BEIJING ACCORDING TO EUROPEAN STANDARDS

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Abstract

In the framework of a publicly-funded program for the seismic assessment of Swiss federal properties in foreign countries, an existing 20-floor concrete shear wall building constructed in the 1990s in Beijing, China, was assessed regarding its seismic safety. This building has long concrete shear walls in the two orthogonal directions. Most of the shear walls have non-planar sections. Shear walls are essentially the only vertical structural members of the building. This is a structural configuration often used in China even in areas with moderate seismicity due to strict low inter-storey drift requirements imposed from Chinese standards when designing for earthquakes. The evaluation of the building was conducted according to European standards. Two methods of assessment, one using a modal response spectrum analysis and one using a displacement-based approach, were applied for the building. A nonlinear finite element analysis program that uses a smeared, rotating-crack formulation for reinforced concrete was used for the pushover analysis of the building. Differences between European and Chinese standards with regard to the design of concrete buildings and the seismic design philosophy in general, concerning e.g. the spectral form and the earthquake design levels, are addressed. Even though this building seems at first view to comfortably meet modern seismic design prescriptions, the results show that the building cannot withstand the total seismic code actions. This is mainly due to low shear strength. The seismic performance of the building is assessed and the vulnerability of this kind of structures designed and built with previous seismic codes of China is discussed.

Keywords: existing shear wall building; nonlinear static analysis; code differences.

1. Introduction

In Switzerland the seismic risk was underestimated for a long time. Appropriate seismic requirements exist in Swiss building code only since 1989 and a large majority of the existing buildings was therefore designed without any seismic considerations. Based on this situation, Swiss government started in 2001 a comprehensive seismic assessment program of its own buildings stock. This includes not only buildings in Switzerland but also buildings in foreign countries such as Swiss embassies and consulates. Within the framework of this program, an existing 20-floor reinforced concrete shear wall building constructed in the 1990s in Beijing, China, was assessed regarding its seismic safety. The FOCL, Federal Office of Construction and Logistics (OFCL in French), wants all or at least the federal properties in the regions with moderate to high seismicity assessed for their seismic safety. The seismic evaluation of these buildings has to be conducted according to European standards, Swiss and EC8 when applicable. Two methods of assessment, one using a modal response spectrum analysis and one using a displacement-based approach, were applied for the considered building. Differences between European and Chinese standards with regard to the design of concrete buildings and the seismic design philosophy in general, concerning e.g. the spectral form and the earthquake design levels, are addressed. The seismic performance of the building is assessed and the vulnerability of this kind of structures designed and built with previous seismic codes of China is discussed.

2. Description of the shear wall building

The shear wall building investigated is situated in Beijing. It is a residential building with 20 stories and two basements. The building was constructed in 1996. Fig.1 shows a general view of the building.

The plan shape of the buildings is almost rectangular, with outside dimensions of 30 m by 25.5 m, Fig.2. The typical floor height is equal to about 3.0 m. The height of the ground floor is equal to about 4.1 m. The total height is approximately 61.1 m above ground level.

The load bearing structure of the building consists of long reinforced concrete walls in the two orthogonal directions with reinforced concrete floors. Most of the shear walls have non-planar sections. Lateral support and resistance to vertical loads is provided by the walls. Shear walls are essentially the only vertical structural members of the building. This is a structural configuration often used in China even in areas with moderate seismicity due to strict low inter-storey drift requirements imposed from Chinese standards when designing for earthquakes. Structural beams of moderate dimensions are provided above these openings. The building has two basements constructed with reinforced concrete.

Fig. 1 – General view of the 20-floor concrete shear wall building

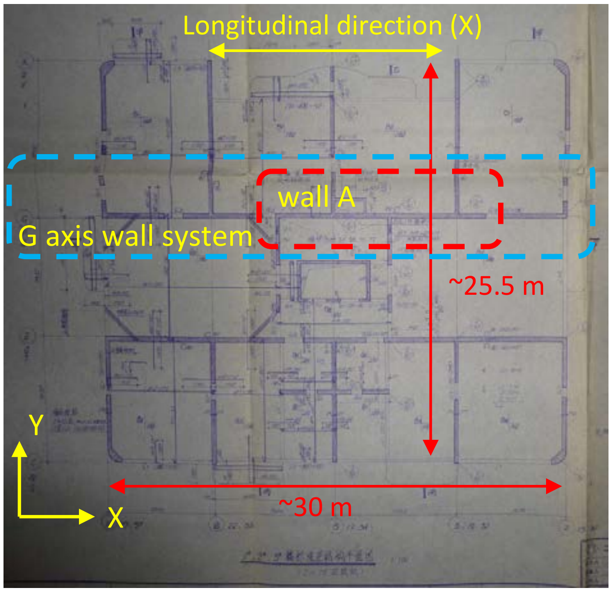


Fig. 2 – Typical floor plan view of the building

3. Seismic loading

The response spectra in the Chinese code are of a different type than those in the Eurocodes and also the values of the pga given for any site cannot directly be compared. As the assessment was performed according to European standards, a transformation of the spectra was necessary. According to Chinese seismic standards [1], Beijing is located on the seismic zone 8 of the seismic hazard map of China. This area is characterized by a peak ground acceleration of 0.20 g. This acceleration corresponds to a moderate (design) earthquake. A moderate earthquake corresponds to a return period of about 475 years. This value does not correspond to the pga on a rock site but rather to a soil class between Class B and C of the EC8 standard [2] according to the study [3]. An EC8 spectrum, proposed by a report of the consulting firm Resonance [4], was used for the assessment of the building. Therefore, in order to calculate the peak ground acceleration a_{gd}, the value of 0.20 g was divided with a soil factor S = 1.15. In the framework of this study this building was assigned to building class CO II as per the Swiss code SIA 261 [5], the structure class that corresponds to an importance class III as per EC8 and an importance factor of γ_I=1.2 as per EC8. According to a geotechnical report found, a soil class C can be attributed to the site of the building. As per the Resonance report [4] a value of T_D = 4 s was chosen. Chinese code response spectra do not adopt a T_D period, beyond which the spectral displacement remains constant.

Fig. 3 and Fig.4 show the elastic acceleration and displacement response spectrum respectively for soil class C. As a comparison, the same figures show the spectra that correspond to a seismic zone 8 and a soil class III as per the Chinese code [6]. The spectrum used for the assessment of the building is a little more conservative at the period range of the building, assuming the same return period of about 475 years.

From older [7] Chinese seismic codes to the most modern ones [6], buildings are initially designed using the spectrum that corresponds to a frequent earthquake. For some categories of building types, drift limitations are imposed for this earthquake level. The derivation of the seismic demand at this stage is effectuated using linear analysis. Finally, drift limitations should be respected for some categories of building types for a seismic demand from a rare earthquake. A non-linear time-history analysis has to be used for this final check. Fig. 5 shows the elastic acceleration response spectrum for the frequent, design and rare earthquake for a seismic zone 8 and a soil class III as per the Chinese code [6], assuming an importance factor of γ_I = 1. It has to be noted that older codes, e.g. [7], and in some cases also the modern ones, were not imposing a drift limit for shear wall type buildings and for the rare earthquake level. Hence, especially before the update of the code after 2001, shear wall buildings in general were designed only for a frequent earthquake. Frequent earthquake is approximately 3 times smaller than the design earthquake. One could argue that Chinese code implicitly assumes a behavior factor of approximately 3. EC8 imposes similar behavior factors for uncoupled wall systems designed for medium ductility. For conservative reasons, mainly due to uncertainties related to the quality of materials, their characteristics and their compliance with European codes, it was decided to use a behavior factor of q=1.5 for the seismic assessment of the building with the forced based assessment method that was initially performed.

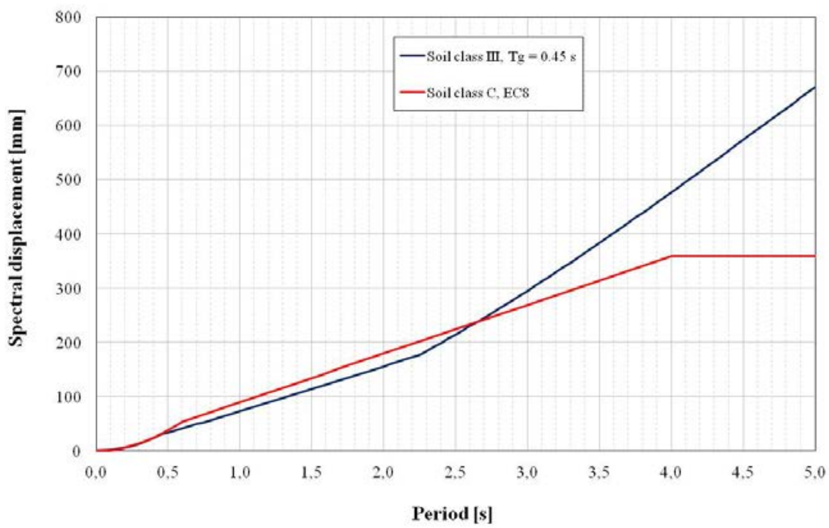


Fig. 3 – Elastic displacement response spectra, a_{gd} = 0,174 g, soil class C as per EC8 and a_{gd} = 0.20 g, soil class III as per Chinese seismic code, for importance factor γ_I = 1.2, viscous damping ratio ξ = 5%

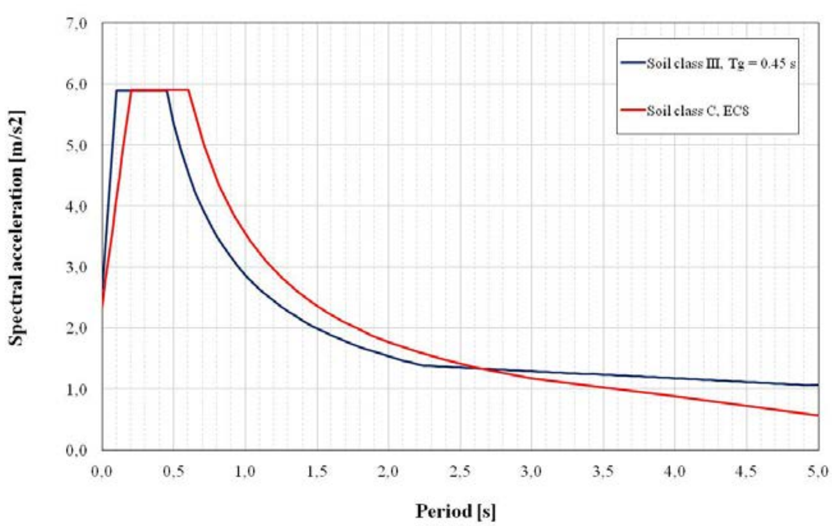


Fig. 4 – Elastic acceleration response spectra, a_{gd} = 0,174 g, soil class C as per EC8 and a_{gd} = 0.20 g, soil class III as per Chinese seismic code, for importance factor γ_I = 1.2, viscous damping ratio ξ = 5%

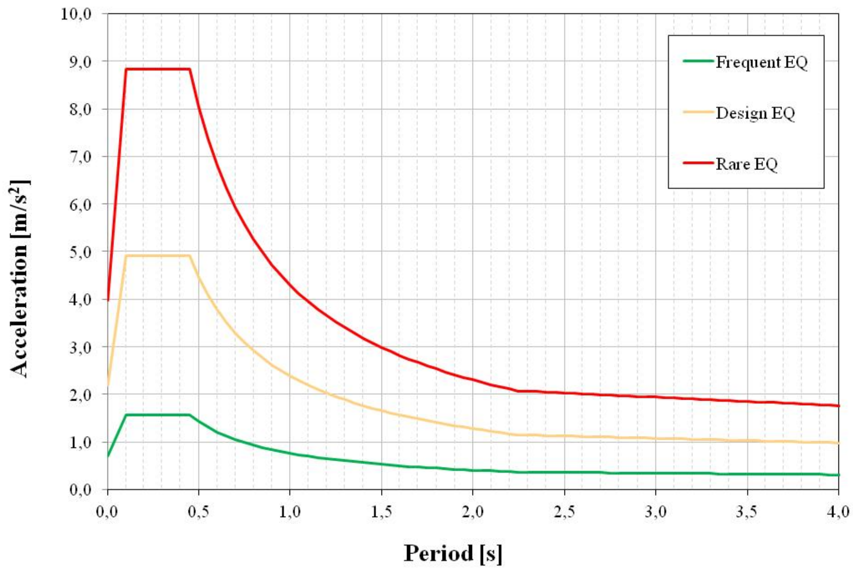


Fig. 5 – Elastic acceleration response spectra as per Chinese seismic code for frequent earthquake, maxSA = 0.16g, design earthquake, maxSA = 0.5g, and rare earthquake, maxSA = 0.90g, soil class III for importance factor γ_I = 1.0 and viscous damping ratio ξ = 5%

4. Structural analysis

4.1 Assessment methods

Two methods of assessment, one using a response spectrum analysis and one using a displacement-based approach, were applied for the building.

A response spectrum analysis was performed for the global building with the software ETABS 2013, CSI America [8]. For this method, seismic forces are distributed in proportion to the rigidities of the elements. Furthermore, the value of the non-cracked concrete elastic modulus for walls and slabs used was equal to E_{cm} = 30,000 MPa. The stiffness of the elements was reduced to take into account the cracking of concrete elements. In general, the stiffness was reduced to 30% and 25% compared to the uncracked state for walls and slabs respectively.

The reinforcements are considered based on information provided by the reinforcement plans available. Since not all the plans were available, when data were missing, realistic assumptions were made for the configuration and the material of the reinforcement.

The response spectrum analysis was used to estimate the natural modes and periods of buildings and to make a first assessment of the most critical elements. Moreover, the period of this model was used to estimate the seismic displacement demand for the displacement-based method used subsequently.

Pushover analysis with Vector2 software [9] developed at the University of Toronto, based on the "modified compression field theory", was carried out to check the walls of the building with a displacement-based approach. The default values of the software were used for all the parameters. In the longitudinal direction of the building, due to, approximate, symmetry of the building, one of the two main wall systems in the longitudinal direction of the building was only modeled, see light blue dotted line in Fig.2. Seismic safety is evaluated by comparing the building's capacity curve with seismic demand according to the adopted response spectrum. This comparison is graphically illustrated in ADRS spectrum diagram format.

In this paper, the documentation of the seismic safety of the building in the transversal direction, being less critical, and for the nonstructural components of the building has been neglected.

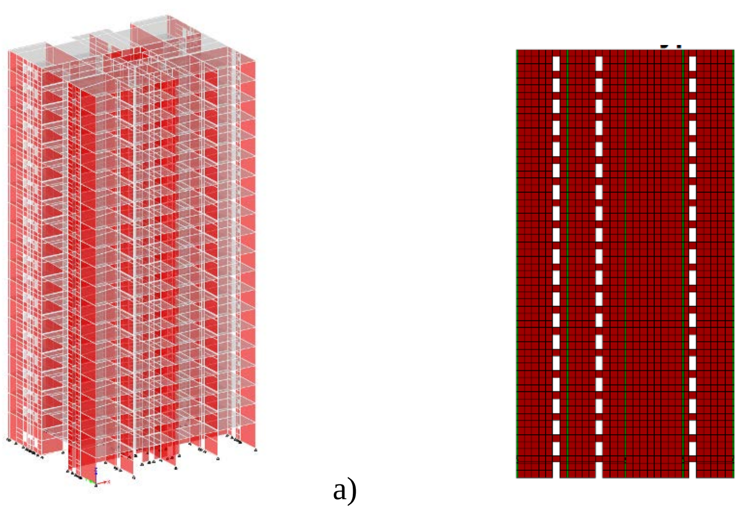
4.2 Modeling assumptions

Fig. 6a shows the 3D model used within the framework of the response spectrum analysis using the software ETABS 2013. The building was assumed fixed at the level of ground floor. The beams above the doors / openings of smaller length have been neglected in this model because it was considered that during the earthquake these beams will be heavily damaged. The construction plans found are not showing any diagonal reinforcement inside these beams. The typical floor seismic mass considered was equal to 872 t.

Fig. 6b shows the 2D model of the wall system along the axis G used for the pushover analysis using the software Vector2. The actual reinforcement of the walls was considered for the verification of this wall. As an approximation, the flanges of the wall system, the walls perpendicular to axis G that are connected with the wall elements along the axis G are considered concentrated along the height of the wall system with a constant width that corresponds to a length of 5 m, even if in some cases the effective length of the flanges were greater than 5 m. This simplification was used for not making the model too stiff and for not overestimating its flexural strength.

4.3 Assessment on the technical specifications SIA 2018

The assessment of the building was based on the SIA 2018 technical specifications [10]. SIA 2018 technical specifications provides an assessment based on the risk by determining the compliance factor (α_{eff}) which is the ratio of the strength of the examined structure and the required strength for a new building. A structure that resists the requirements of SIA standard 261 has a compliance factor of 1. In accordance with technical specifications SIA 2018, interventions are needed if the compliance factor is below a threshold value of α_{eff}, fixed α_{min} = ¼ for importance classes CO I and CO II, importance classes II and III as per EC8. In that case the individual risk is unacceptable. If the compliance factor is greater than α_{min}, interventions must be implemented if they are proportionate. A measure may be considered proportionate if the associated costs do not exceed 10 Mio. Swiss Francs per human life saved. This corresponds to what the society is willing to invest to save a human life.



a) b)

Fig. 6 – a) General view of the 3D model used for the response spectrum analysis,

b) View of the 2D model of the G axis wall system used for the pushover analysis

5. Results

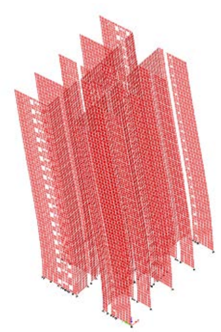
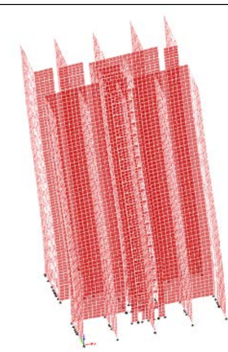
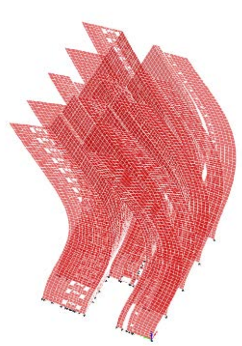
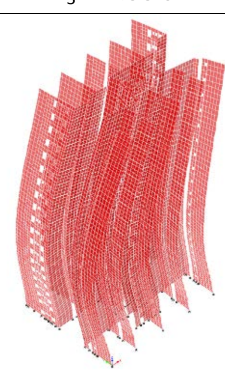
5.1 Response spectrum method

The modal masses of the most important modes in the longitudinal (x) and transversal (y) direction of the building obtained with ETABS 2013 are given in Table 1. The vibration modes 2, 4, 5 and 6 are shown in Table 2. Globally, the shear forces, obtained in each direction at the base of the structure for a q=1.5, are approximately the following: Vx = 23'900 kN, Vy = 20'450 kN.

Table 1 –Modal masses (%), directions x and y

Mode	Period [s]	Modal masses (%)	
		direction x	direction y
2	1.67	5	64
3	1.33	67	5
5	0.42	1	16
6	0.37	14	2

Table 2 –Main vibration modes

	
T_2 = 1.67 s	T_3 = 1.33 s
	
T_5 = 0.42 s	T_6 = 0.37 s

5.2 Discussions of the initial results and of the structural concept

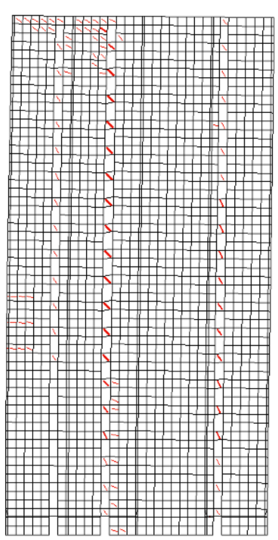
The presence of openings in the walls of the buildings divides the wall system to smaller wall elements. Some of them have planar and other non-planar section. One of the main seismic deficiencies of the building in the longitudinal direction is the concentration of the forces to approximately two walls with non-planar section, the ones with the bigger stiffness; one of them is the wall A as shown in Fig. 2. Therefore, the shear strength of the building comes mainly from the shear strength of the web of these two stiff walls whose length is a fraction of the total of 30 m long dimension of the building. Simplified calculations showed that the ratio of the shear strength to the shear demand of the walls is smaller than equivalent ratio for the flexural strength of the walls, implying that a brittle failure is governing the seismic behavior of the building. Furthermore, the shear strength corresponds approximately to a third of the shear demand, from the elastic spectrum, and may be therefore considered to be associated to a behavior factor greater than 3. A pushover analysis of the G axis wall system performed, in order to verify the findings from the response spectrum method.

5.3 Pushover analysis

For the analysis of the walls with Vector2, the vertical loads were applied on each floor. A displacement up to 400 mm was applied to the top of the walls.

For a displacement of 0.1 x 400 = 40 mm at the top of the walls, the beams above openings are overstressed, see Fig. 7a. For a displacement of 0.32 x 400 = 128 mm at the top of the walls, the maximum resistance to horizontal force is reached for a value of approximately 8'780 kN, see Fig. 7b.

To create the ADRS curve, see Fig. 8, the displacement that corresponds to a force of 8'780 kN is assumed equal to 128 mm / Γ (~ 1.5) = 83.33 mm. The force of 8'780 kN corresponds to an acceleration of 1.31 m/s^2. This acceleration corresponds to a secant stiffness with a period of 1.4 s, see ADRS diagram in Fig. 8. This value matches well with the period of the first mode in this direction calculated with ETABS 2013. For a period of 1.4 s, the acceleration demand is of the order of 2.5 m/s^2. After a top displacement of 128 mm, the coupling beams are heavily stressed and the model showed that yielding of both the shear and longitudinal reinforcement of the wall A takes place that is accompanied with a significant drop of the base shear strength of the G axis wall system. For the purposes of the assessment of the building, it was assumed that after this point the building is heavily damage with no repairable damages. Hence, the compliance factor α as per SIA 2018 is approximately α_{eff} = 1.31 / 2.5 ~ 0.5.



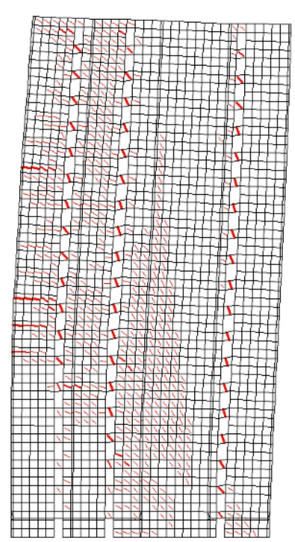


Fig. 7 – a) Deformation and cracks direction for a displacement of 40 mm at the top of the walls, b) Deformation and cracks direction for a displacement of 128 mm at the top of the walls

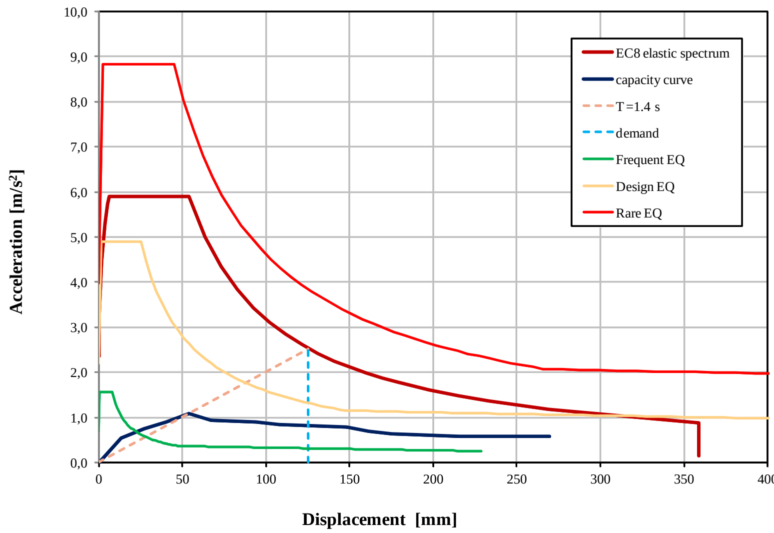


Fig. 8 – Capacity curve - ADRS axis G walls

5.4 Discussions of the final results

Since the compliance factor for the building α as per SIA 2018 is above the limit of α_{min} = ¼, strengthening of the building should be proposed only in the case that simple and cost effective measures can be applied. It was considered that heavy strengthening measures should be implemented in order to increase substantially the seismic strength of the building and that a compliance factor of α_{eff} ~ 0.5, even if it is not an acceptable value for a new building, it is acceptable for the existing building studied.

It has to be noted that the seismic level used for the assessment of the building was greater than the one probably used for the design of the building. This difference is, first of all, due to differences between the spectrum form between the EC8 and Chinese seismic codes and due to the utilization of an importance factor of γ_I = 1.2.

Nevertheless, according to the ADRS diagram of Fig. 8, even if the building resists the seismic demand for the frequent earthquake, it seems that for the occurrence of a design earthquake the building will suffer substantial damages that probably will not be repairable and hence it will not respect the performance criteria for the design earthquake that imposes that any damage for this earthquake level should be repairable, see [11].

Some simplifications were made for the numerical model and a quite conservative failure criterion was adopted for the assessment of the building. Nevertheless, given the fact other factors influencing the seismic behavior of the studied structure were not taken into account, e.g. the cyclic behavior of the building, the influence of the higher modes etc, some conservatism seems acceptable and justified. To continue with the previous discussion, it is doubtful that the building can meet the performance criteria for the rare earthquake level: no collapse or serious damage that can create hazard to life safety as per [11].

6. Acknowledgements

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7. Conclusions

This study presents the findings of the seismic assessment of an existing 20-floor concrete shear wall building in Beijing, China, using two methods, a conventional forced-based assessment method and a more sophisticated displacement-based method. Even though this building seems at first view to comfortably meet modern seismic design prescriptions, the building has numerous long concrete shear walls in the two orthogonal directions; the results show that the building cannot withstand the total seismic code actions. This is mainly due to low shear strength of the coupling beams and of the global structure. After the yielding of some elements, the forces seem to be concentrated to the stronger and stiffer elements that cannot withstand the total seismic forces.

Even if the seismic demand, mainly due to Swiss Federal requirements, used for the assessment of the building is greater than the one used initially for the design of the building, it seems that it cannot meet the performance criteria at least for the design and rare earthquake levels as per the local Chinese seismic codes. It seems that similar buildings designed with older seismic codes, before 2001, but even in case of some structure types designed with more modern codes may have the same structural deficiencies and hence their seismic behavior will not be satisfactory.

Some conservatism adopted for the assessment of the building of this study seemed reasonable. Nevertheless, an even more detailed analysis that takes into account the full geometry of the building, the influence of the higher modes and that uses a more sophisticated analysis, e.g. non-linear time history analysis could give an even better insight of the seismic performance of the building for the various earthquake levels.

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