



Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

CROSSH: China Resilience of Schools to Seismic Hazard

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ABSTRACT

The Comprehensive School Safety Framework (2017) is funded on three pillars: ‘*Safe Learning Facilities*’, ‘*School Disaster Management*’, and ‘*Risk Reduction and Resilience Education*’. CROSSH, funded by the International Center for Collaborative Research on Disaster Risk Reduction (ICCR-DRR), at Beijing Normal University, China, aimed at investigating how the three pillars underpinned the process of school infrastructure recovery post-2008 Wenchuan earthquake in China, which caused more than 5,000 school children deaths. The focus here is on Beichuan Qiang Autonomous County, Sichuan. When the M7.9 Wenchuan earthquake struck Sichuan on May 12, 2008, it caused the total or partial collapse of several schools: 1,200 of 2,600 students in the Beichuan Middle School died or were missing due to the building collapse; 500 students in the Beichuan Maoba Middle School died due to the landslides triggered by the earthquake.

This paper summarized the main findings of the CROSSH project, including 1) a methodology for physical vulnerability assessment and its application to school buildings in the County, through new analytical models; 2) an investigation on the enhancement of seismic resilience of schools through retrofitting of school buildings and disaster risk reduction education. The project also investigated perceptions, perspectives and hazard adjustments of Chinese students regarding earthquakes.

In particular, the proposed physical vulnerability assessment methodology consists of a) systematic collection of data on school infrastructure location and characteristics across the County; b) development of a comprehensive database of typical and systematically defined structural typologies, including main structural and non-structural characteristics (age of construction, number of story, lateral load resisting system and materials, number of occupants, etc.); c) development of fragility functions, derived within the project, for the most common structural typology. These tasks have been carried through a desk-study combined with targeted field surveys in Beichuan.

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The field surveys included both old (pre-Wenchuan) and new (post-Wenchuan) school sites, for a total of 102 school buildings visited during the mission. The project team used a pre-designed data collection form and a mobile app developed by the authors within a previous project. Questionnaires to local practitioners on structural engineering aspects as well as to both middle school and university students were also carried out. The aim of the latter was to investigate perceptions, perspectives and hazard adjustments of students regarding earthquakes.



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ABSTRACT

This paper presents the main findings and outcomes of the CROSSH project, including 1) a methodology for physical vulnerability assessment and its application to school buildings in Beichuan Qiang Autonomous County, Sichuan, China, through new analytical models; 2) an investigation on the enhancement of seismic resilience of schools through retrofitting of school buildings and disaster risk reduction education. The proposed methodology for assessing physical vulnerability consists of a) systematic collection of data on school infrastructure location and characteristics across the County, considering both old (pre-Wenchuan) and new (post-Wenchuan) school sites, for a total of 102 school buildings; b) development of a comprehensive database of typical and systematically defined structural typologies, including main structural and non-structural characteristics (age of construction, number of story, lateral load resisting system and materials, number of occupants, etc.); c) development of a fragility functions, derived within the project, for the most common structural typology. Different types of seismic strengthening techniques for selected schools in Beichuan are investigated and the resulting reduction in building fragility is assessed. These tasks have been carried through a desk-study combined with targeted field surveys in Beichuan. Questionnaires to local practitioners on structural engineering aspects as well as to both middle school and university students were also carried out.

Introduction

Children and youth are especially vulnerable in disaster situations due to their age and their developmental stage. Of the estimated 1.2 billion students enrolled in primary and secondary school worldwide, 875 million children are enrolled in high seismic risk zones, while millions also face regular flooding, storms, landslides, and fires. Those children are spending up to 50% of the waking hours in school facilities that are often neither designed/constructed nor maintained to be safe and natural-hazard resilient. Several considerations set school facilities apart from other public and private buildings in terms of priority for multi-hazard risk assessment and for the design/implementation of multi-hazard resilience-increasing interventions: 1) school facilities are the only high-occupancy public buildings (other than prisons and courthouses) whose occupants are compelled by legal mandate to be inside them; 2) students are considered to be a particularly vulnerable population; 3) school facilities in many communities tend to remain in use longer than comparable structures in private

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ownership, and tend to receive less frequent and less consistent capital renewal investment; 4) community members and public officials often hold a high (if unfounded) expectation that school facilities will provide community shelter or host public services in the wake of a natural disaster; 5) the collapse of school facilities is particularly devastating to communities because schools can hold an entire generation (i.e., all children of a certain age-range in the community), a community's future.

The impact of natural hazards to children and youth and to the education system are especially dire in the Asia-Pacific region. According to the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), the region is home of 750 million young people aged 15-24 years old; 25.3% of the region's population is under 15 years old. The region is notoriously the most hazard-prone in the world, where children and the young are disproportionately affected by natural hazards. It is also predicted to be one of the most affected regions by the projected impact of climate change. Unreinforced masonry and under-reinforced concrete are commonly used structural material for school facilities in many Asia-Pacific countries, especially in the past few decades. These structural types have inherent serious vulnerabilities to ground shaking and extreme loads (e.g., wind-induced), particularly in places where building codes lagged behind current scientific structural and earthquake engineering knowledge.

The Comprehensive School Safety Framework (2017) [1] is an integrated approach to reduce disaster risk and promote resilience in the education sector. It is funded on three pillars: '*Safe Learning Facilities*', '*School Disaster Management*', and '*Risk Reduction and Resilience Education*'. The CROSSH (*China Resilience of Schools to Seismic Hazard*) project, funded by the International Center for Collaborative Research on Disaster Risk Reduction (ICCR-DRR), at Beijing Normal University, China, aimed to investigate how the three pillars underpinned the process of school infrastructure recovery post-2008 M7.9 Wenchuan earthquake in China. Over 7,000 schoolrooms collapsed during the earthquake, mostly in rural areas, reportedly leading to the death of over 5,000 students (though some parents believe the real figure is twice that officially cited) and the injury of over 15,000 students [2]. The total death toll of the quake was around 90,000 people, with some 375,000 injuries [3]. A month after the quake, nearly 20,000 people remained missing, while five million were rendered homeless. The focus here is on Beichuan Qiang Autonomous County, Sichuan: 1,200 of 2,600 students in the Beichuan Middle School died or were missing due to the earthquake-induced building collapse; 500 students in the Beichuan Maoba Middle School died due to the landslides triggered by the earthquake. The disproportionate number of school collapses, especially newly constructed ones, led to open discussions that they were not built to adequate standards. This, in turn, has led to allegations of corruption on the part of Ministry of Education officials and contractors.

After the tragic Wenchuan earthquake, disaster risk reduction (DRR) awareness all over China has been boosted. In 2011, the government put forward the '*State integrated disaster risk reduction and mitigation strategy (2011-2015)*' [4], with school safety being a key focus of the government DRR strategy. This has included DRR integration in school curricula, and particularly teacher trainings and preparedness activities. A number of lessons has been learnt from past earthquakes in China, and particularly the Wenchuan one, also leading to advancements in the seismic design and assessment of school facilities through improved building codes and superior construction supervision, e.g., GB50011-2010 [5]. However, a robust framework for assessing and increasing seismic resilience of school facilities is lacking; no formalized guidance exists on prioritizing interventions and improving

structural capacity of schools, except a few examples of retrofit projects. On the other hand, a substantial body of work exists on analytical vulnerability assessment of structures (and its reduction), in several countries, such Italy [6], and Switzerland [7], among others. Availability and reliability of methods and tools for analytical vulnerability assessment have been reviewed by the Global Earthquake Model [8], providing guidelines for assessing the seismic vulnerability of single buildings and groups of assets. A comprehensive, practice-oriented procedure for performance-based seismic assessment of buildings is also available in the Federal Emergency Management Agency (FEMA) P-58 [9] a repository of fragility functions for structural and non-structural components in the related PACT software. These resources formed the reference framework for assessing the physical vulnerability of schools in the CROSSH project. However, the project aimed at progressing beyond the state-of-the-art by using actual (local) data (e.g., ground motion records, material properties, design practice, etc.), high fidelity building models for nonlinear dynamic analysis, multiple-criteria decision-making for resilience improving solutions in the specific regional context.

Apart from assessing the physical vulnerability and proposing ‘hard’ risk mitigation measures (e.g., seismic retrofitting) for school facilities, analysis of the social vulnerability and ‘soft’ risk mitigation measures (e.g., DRR education) play a key role in increasing natural-hazard resilience, particularly within local communities [9]. Therefore, the CROSSH project also aimed at assessing student perceptions, awareness and preparedness level in terms of knowledge/skill/attitude towards earthquake. This analysis reveals that: earthquake experience has a larger impact than gender regarding perceptions; gender factor is advantageous in dominating people’s perspectives/awareness of earthquake risk; neither gender factor nor earthquake experience alone can lead to significant differences in student hazard adjustments about earthquakes.

Physical Vulnerability Assessment

Field Investigation

In order to construct a database of school facilities in Beichuan Qiang Autonomous County, Sichuan, a two-week field investigation has been carried out in June 2017. Sichuan is the fourth populous provinces in China with a population of more than 80 billion in 2010. It’s also one of the most seismically active regions with a history of devastating earthquake events, e.g., the 2008 M7.9 Wenchuan earthquake and 2013 M6.6² Lushan earthquake.

A rapid visual survey form, designed by Nassirpour et al [11] and implemented in a mobile application, has been used for the data collection during the survey. Based on seven school sites in Beichuan County and five in Mianyang City, as shown in Fig. 1, a total of 102 school buildings have been surveyed. The information collected during the field investigation consists of general structural characteristics, such lateral-load resisting system and its materials, age of construction, number of stories, type of foundation, presence and type of infill walls, type of openings and floor slabs, along with characteristics of the roof, etc. Furthermore, depending on the structural system and material, the most common structural deficiencies have been identified, particularly when looking at seismic vulnerability. These included the potential pounding effects, presence of soft-story, presence of strong-beams weak-columns, various irregularities (plan, elevation and openings), etc. For framed structures,

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dimensions of columns and beams have also been measured and the type and material of infill walls have been estimated. A confidence level was assigned to each collected parameter.



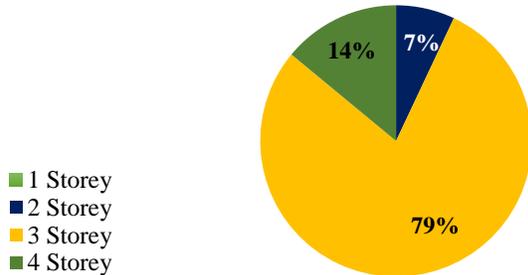
Figure 1. Location of the surveyed schools in Beichuan County and Mianyang City.

Based on the field investigation, all surveyed school buildings in Beichuan County have been previously destroyed (partially or completely) during the 2008 Wenchuan earthquake. The school sites have been relocated and reconstructed after the disaster, with financial support from worldwide. The new school buildings have been designed and built after the 2008 Wenchuan earthquake, according to the new Chinese seismic code, i.e., GB50011-2010. The construction year was obtained mainly through interviewing locals. Statistical representations of the collected data on schools are illustrated in Figure 2 and 3.

As shown in Fig. 2, the most common type of primary lateral-load resisting system for Chinese school buildings is RC frame with RC slabs and three stories. Most of the new school buildings present good overall conditions (Fig. 3). For each building block, the average number of bays in x- direction is seven while the average number of bays in y- direction is two. This information is used as reference to define a school index building (to follow). For most of the teaching buildings, the average classroom spans two bays in x- direction and one large bay in y- direction. Large opening is commonly observed at stairs. According to the survey results, about 14% of school buildings are built on slope, with potential susceptibility to landslides triggered by earthquake events; about 43% of school buildings are susceptible to pounding, i.e., they have buildings closer than 0.2m. A critical factor observed in most of the surveyed school buildings is the typical regional practice of having long, open corridors outside

classrooms, running through the entire floor. Consequently, the interior bay is much narrower than the exterior one due to the presence of the corridor, resulting in plan irregularity.

Number of Stories



Primary Structural System

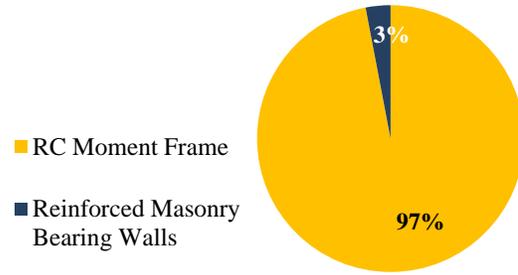
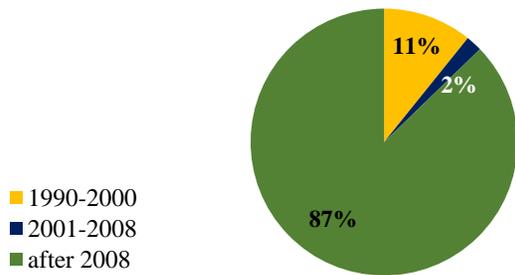


Figure 2. Statistics on number of stories and primary structural systems of surveyed schools in Beichuan County.

Construction Year



Structural Condition

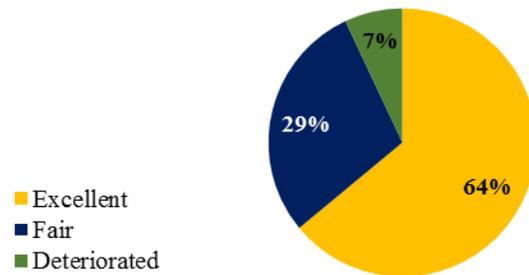


Figure 3. Statistics on construction year and structural condition of school buildings in Beichuan County.

Selection, simulated design and nonlinear modelling of school index building

Based on the data collected during the field survey, an index building has been selected to represent the most typical school buildings in Beichuan County. The selected index building is a 3-storey RC frame with inter-story height of 3.5m. Since most of the school buildings in Beichuan are built after 2008, the index building is designed according to the current Chinese seismic code, i.e., the GB50011-2010 with seismic fortification intensity (SFI) of 7 (0.15g) and class II soil (medium-stiff soil site with equivalent shear wave velocity of 250-500 m/s and a site soil layer thickness greater than 5m). In the Chinese codes, the SFI is regarded as main criterion of seismic design, corresponding to a basic seismic intensity. The basic seismic intensity of a certain region in China is defined as the impact of the earthquake with 10% probability of exceedance in 50 years (i.e., with a mean return period of 475 years), divided into 12 degrees. Each SFI is associated to different design peak ground acceleration (PGA), resulting in six groups. The PKPM software (in its 2010 version), widely used in China's structural engineering industry, is used to design the index buildings. The 3D view of the index building is illustrated in Fig. 4. With the aim of reducing the computational effort, the main central frame in each direction is extracted and used as structural model for the vulnerability analysis in the next subsections (Fig. 4). Beams have rectangular cross-sections with dimensions of $500 \times 300 \text{mm}^2$ in x-direction and $650 \times 300 \text{mm}^2$ in y-direction. Columns are with dimensions of $500 \times 500 \text{mm}^2$ in both

direction. The material property for concrete is C30 with compressive strength (f_c) of 2×10^4 kPa and modulus of elasticity (E_c) of 3×10^7 kPa. As for the reinforcement, steel of grade HRB400 is used, with yield strength (f_y) of 4×10^5 kPa and modulus of elasticity (E_s) of 2×10^8 kPa. Due to limited space, the reinforcement detailing is not listed in this paper but can be found in [12].

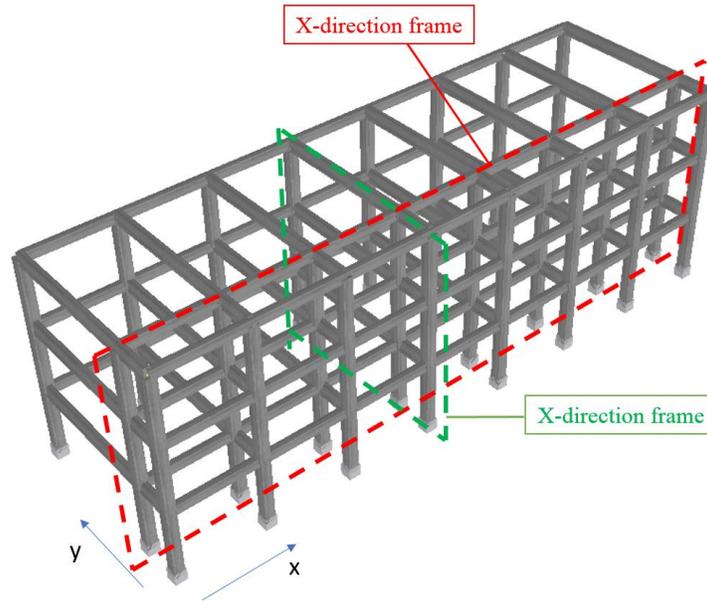


Figure 4. Perspective view of index building

The extracted 2D frames are modelled using SeismoStruct finite element software **Error! Reference source not found.**[13]. The program allows the construction of finite element models with consideration of both material inelasticity and geometric nonlinearities. Details on the nonlinear modelling can be found in [12]. The structural fundamental periods are 0.19s and 0.17s in x- and y-direction respectively.

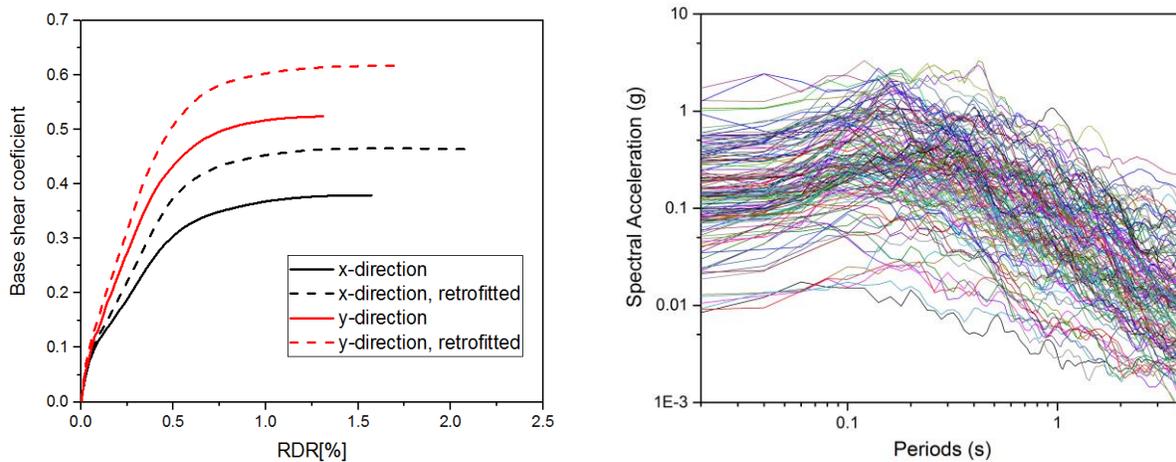


Figure 5. Capacity curves for the 2D frames in x- direction and y- direction (left), and response spectra of the 146 ground motion records from the 2008 M7.9 Wenchuan Earthquake; the 2013 M6.6 Lushan Earthquake; and the 2017 M6.5 Jiuzhaigou Earthquake (right).

Conventional nonlinear static pushover analysis is performed to examine the lateral deformation and damage pattern of the considered structure into the inelastic range of behaviour. An incremental uniform rectangular lateral loading is applied at the side nodes at each floor. This loading pattern is able to highlight irregular response features such as soft-story and able to obtain the softening post-peak branch of the response, if any. The capacity curves of the two considered frames are shown in Fig. 5 (left). For these curves, the base shear is normalized with respect to the total seismic weight of the frame to obtain the base shear coefficient; the roof displacement is divided by the structural height to obtain the roof drift ratio. These curves provide a representative and visually effective illustration of the Beichuan school building portfolio structural properties.

Fragility analysis

Fragility curves are a key component of probabilistic seismic risk assessment. They express continuous relationships between a ground motion intensity measure (IM) and the probability that the specified structure will reach or exceed predefined damage states (DSs). In general terms, a fragility curve is built by fitting a statistical model to data on building damage at different values of the IM, for example based on post-earthquake surveys. In the case of analytical fragility curves, structural response is first obtained through the analysis of structural models subjected to earthquake excitation of various/increasing intensity. The structural response obtained is expressed in terms of engineering demand parameters (EDPs), which are then compared to properly calibrated thresholds (still in terms of EDPs) associated with a given damage state or performance level of structural and nonstructural components and systems. The number of structural analyses required to construct the fragility curve may be large if both variability in the structural model/capacity (i.e., modeling uncertainty) and ground motion characteristics are included. Hence, a number of approaches for fragility curve generation have been proposed in the past that either adopt a simplified structural model (e.g., a single degree of freedom - SDoF - system), analysis approach (static or dynamic), assessment method or combination of these. These have been extensively reviewed in [8].

In this study, a suite of nonlinear time history analysis (NLTHA) simulations is conducted using ‘*Cloud Analysis*’ [14], which is based on a simple regression in the logarithmic space of structural response (i.e., the EDPs from NLTHA) versus IMs for a set of recorded ground motions (unscaled). This allows to estimate the conditional mean and standard deviation of EDP given IM; the latter is assumed to be constant with respect to IM over the range of IMs in the cloud. The use of logarithmic transformation indicates that the EDPs are assumed to be conditionally lognormally distributed (conditional upon the values of the IMs); this is a common assumption that has been confirmed as reasonable in many past studies. In this study, the spectral pseudo-acceleration corresponding to the first-mode elastic vibration period, $S_a(T_1)$, for a damping ratio of 5%, is chosen as an IM. Specifically, an equivalent SDoF inelastic oscillator system is used to model the nonlinear structural response of the original multiple-degree of freedom (MDoF) frames. The nonlinear force-deformation law governing the SDoF’s response to monotonic lateral loading is implemented by idealizing the MDoF push-over curves into the SDOFs backbone curves. Equivalent SDoF oscillators are modelled in OpenSEES [15] with hysteretic material model to construct a uniaxial bilinear hysteretic material object with pinching of force and deformation.

Unscaled ground motion records from recent earthquakes occurred in the Sichuan province are used as input to carry out NLTHA. Taking advantage of data from the 2008 M7.9 Wenchuan Earthquake; the 2013 M6.6 Lushan Earthquake; and the 2017 M6.5 Jiuzhaigou Earthquake, a total of 146 real records have been used as input for the cloud analysis. Those record are characterized by values of the Joyner-Boore distance (shortest distance from a site to the surface projection of the rupture surface) less than 100 km. This provides a statistically significant number of strong-motion records of engineering relevance for the applications of this study, without introducing large scaling factors. Fig. 5 (right) show the response spectra of the 146 ground motion records.

The Chinese seismic design code GB 50011-2010 describes four possible damage states for buildings, each characterized by relevant global deformation values, as given in Table 1. Specifically, ΔU_e represents the maximum inter story drift ratio (MIDR) of structures in the stage of elastic deformation. ΔU_p stands for the MIDR in range of inelastic deformation. Based on the description of damage state criteria in Table 1, damage thresholds have been defined in MIDR and the corresponding values are given in Table 2.

Table 1 Damage states defined in GB50011-2010

Damage states	Descriptions	Deformation (MIDR)
Slight damage	5% of structural elements have minor cracking; minor damage to non-structural components.	$(1.5\sim 2)\Delta U_e$
Moderate damage	30% of structural elements have extensive cracking; severe damage to non-structural components.	$(3\sim 4)\Delta U_e$
Extensive damage	More than 50% structural elements have extensive damage or partially failure of columns and beams.	$<0.9\Delta U_p$
Collapse	Significant failure of columns and beams	$>\Delta U_p$

Table 2 Values assigned for different damage states in terms of MIDR for each model

Structural Description	MIDR Threshold			
	Slight	Moderate	Extensive	Collapse
x-direction, original	0.61%	1.21%	1.85%	2.35%
x-direction, strengthened	0.74%	1.49%	2.48%	3.95%
y-direction, original	0.47%	0.95%	1.73%	2.09%
y-direction, strengthened	0.69%	1.36%	2.05%	2.64%

Analytical fragility functions have been finally derived through the least square method [16]. Figure Fig. 6 illustrates the fragility curves derived for the 2D index buildings in both directions. The obtained fragility curves show that the index building designed based on the current Chinese seismic code is characterized by relatively low vulnerability. Specifically, according to GB5001-2010, structures designed with a SFI of 7 (0.15g) are characterized by a maximum horizontal seismic influence coefficient of 0.12g for a frequent earthquake (mean return period, $T_R = 60$ years), 0.34g for the design earthquake ($T_R = 475$ years) and 0.72g for a rare earthquake ($T_R = 2475$ years). The corresponding design spectrum can be derived for each T_R . Since the index building periods in both directions are in the range of the response spectrum plateaus, the corresponding $S_a(T_1)$ are 0.12g, 0.34g

and 0.72g for the considered T_R . As a result, according to Fig.7, for frequent earthquake events, the probability of observing any damage for the index building is about zero. For $T_R = 475$ years, there is around 27% of chance of slight damage and less than 10% of chance of moderate damage. The probability of extensive damage or even collapse is negligible. For rare earthquake events, there is around 50% of chance that the building will suffer slight damage. The probability of extensive damage is around 8% for both directions while the probability of collapse is almost negligible. As a result, index buildings designed to current seismic design code GB5001-2010 presents good overall seismic performance across a range of relevant ground shaking intensities.

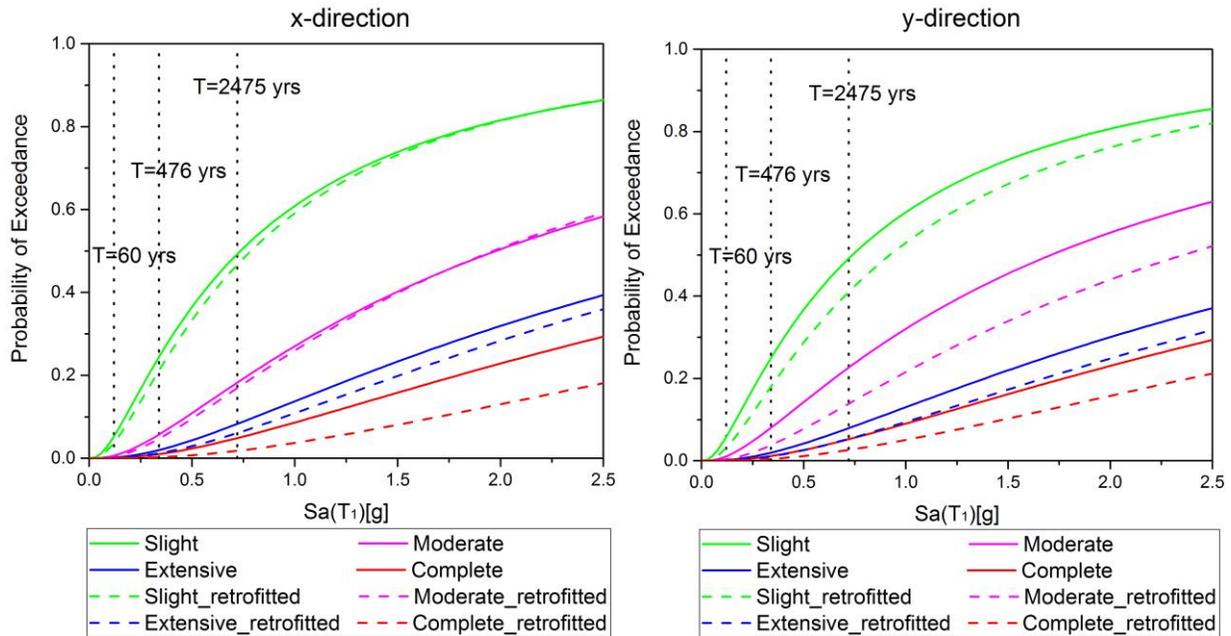


Figure 6. Fragility curves of the 2D index building in x- direction and y- direction

Seismic Retrofitting

To increase the seismic resilience of school buildings in Beichuan, apart from collecting detailed building information, interviews have been carried out to investigate the local practice in terms of retrofitting technologies in the Sichuan Province. Four local experienced construction engineers and one structural engineering professor from a local university have been interviewed. The interviews consists of three main parts, aiming at collection information on: 1) most common deficiencies of RC buildings; 2) most widely used retrofitting techniques, and 3) practical application of retrofitting methods. The results highlight that load path, structural strength, stiffness, ductility, configuration and foundations should be all considered in the retrofitting process. Beams are usually retrofitted by carbon fiber reinforced polymer (CFRP) and steel jacketing (bonded steel plate and wrapped steel), while columns are mostly retrofitted through concrete jacketing. For RC walls, steel mesh with ferrocement are typically use. Seismic isolations and dampers are also used in the area; however, due to their relatively high costs (installation, maintenance), they are not as widely used as the above-mentioned methods.

Although the considered index building is characterized by good overall seismic performances across a range of relevant ground shaking intensities, an illustrative application of typical seismic retrofitting strategies is briefly presented. This exercise represents a very preliminary investigation on the possible improvement of structural performance. Specifically, two most widely used retrofitting methods are applied: concrete-jacketing is applied to all the first-storey columns (for both frames) and CFRP is used for beams. According to the *Technical Code for Infrastructure Application of FRP Composites* (i.e., GB 50608-2010; [17]), a layer of CFRP with tensile strength of 3×10^6 kPa, tensile modulus of 2×10^8 kPa is chosen to improve the flexural capacity of the first-storey beams along x-direction. The concrete jacketing is designed according to the *Chinese Code for Design of Strengthening Concrete Structures* (i.e., GB 50367-2006; [18]). Concrete C30 is selected in this retrofitting. Additional concrete thickness of 100mm and six HRB 400 rebar with diameter of 16mm are added to the ground-floor column sections.

Using the same criteria and analysis methods as in the previous section, the MIDR threshold values after retrofitting, for each considered damage state are first computed (Table 2) based on the new derived capacity curves Fig. 5 (left). Fragility curves for the retrofitted frames are finally derived and shown in Fig. 6 (together with the fragility curves of the original frames). In terms of capacity curves, both strength and ductility are increased after retrofitting. The comparison of fragility curves in x-direction, shows that that the considered structural strengthening method has little effects on prevention of slight damage and moderate damage, while it helps to decrease the probability of extensive damage and collapse under rare earthquake. For the frame in y-direction, the retrofitting strategy improve the overall structural performance in terms of different performance demands.

Conclusions

This paper has introduced a framework for assessing the seismic resilience of school facilities in China. The proposed framework consists of both physical and social vulnerability assessment and it is applied, for illustrative purposes, to the Beichuan Qiang Autonomous County, Sichuan. The paper has also introduced a preliminary investigation on the enhancement of seismic resilience of school building through seismic retrofitting. Specifically, the physical vulnerability assessment consists of the following phases: 1) a 2-week field investigation of 102 school buildings in Beichuan County and Mianyang City; 2) the selection, simulated design, and detailed nonlinear modelling of a school index building; 3) the derivation of fragility curves for different damage states, combining nonlinear static analysis (on 2D frames extracted from the full 3D school index building) and nonlinear time history analysis (on simplified, equivalent SDOF systems to each 2D frame). Chinese ground motion records from recent earthquake events have been selected and used to derive fragility curves. FRP and column jacketing have been applied as possible retrofitting strategies to improve the structural performance and reduce school fragility. Through online questionnaire and in-depth interview, student's perception, perspectives and hazard adjustments has finally been explored.

The results of the illustrative applications show that most of school buildings in Beichuan County are designed and built according to the most recent seismic design code (post-2008), and they are characterized by good overall seismic performance (across a range of different ground shaking intensities).

Acknowledgments

The study presented here is funded by the International Center for Collaborative Research on Disaster Risk Reduction (ICCR-DRR). The authors wish to gratefully acknowledge the contribution of Prof. Jingsong Lei (Southwest University of Science and Technology), Mr Jianguo Tong (Sichuan Jianguo Technology Development Co., Ltd), Mrs Quan and Miss Rujia Deng (Mianyang Science and Technology City), Mr Hao Bing (Sichuan University), Mr Tao Li (Ji Zhun Fang Zhong Architectural Design Co. Ltd), and Mr Xinxin Li (China Southwest Architectural Design and Research Institute Corp., Ltd), for the support during the data collection in Sichuan. The authors also thank Prof Qiang Ma, Institute of Engineering Mechanics (IEM), at China Earthquake Administration (CEA), for providing the ground motion records used in this study.

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