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Response of school buildings after the September 2017 earthquakes in Mexico

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Abstract

In 2017, Mexico was struck by the September 7 M_w8.2 Tehuantepec and the September 19 M_w7.1 Puebla-Morelos earthquakes, which caused 477 deaths. In the public-school sector, 19,194 school campuses were damaged: 63% with minor damages, 36% with moderate and moderate/severe damage, and 1% with very severe damage that required building substitution. No casualties were recorded in public school facilities. All prototype school buildings withstood the earthquakes without collapse. Minor damage was observed in 75% of buildings. Damage was concentrated in load-bearing walls in masonry structures, and infill walls in RC and steel frame structures. Heavily damaged RC structures exhibited "short column" distress. Steel structures showed plate buckling due to shear and axial load in columns made up light gage steel members.

The seismic performance of Mexican public schools designed and built with modern regulations, as well as maintained properly, was superior than that of schools with poor design and/or lack of maintenance. A strategy for increasing seismic resistance must consider seismic rehabilitation under modern criteria -design and construction-, as well as a culture of supervised maintenance and sustainable conservation over time.

Common prototype buildings, existing and rehabilitated, were analyzed under linear and nonlinear static procedures. Calculated behavior was consistent with that observed in the field. Compared to seismic design demands, existing structures are likely to exhibit significant damage that could compromise their stability. Rehabilitated structures, conversely, are likely to attain the desired performance level, i.e. immediate occupancy.

Based on observations and data analyses, policy, technical, implementation and sustainability and outreach recommendations aiming at increase schools´ safety and resilience against earthquakes are provided.

Keywords: Schools; seismic rehabilitation; numerical modeling; performance-based design; risk mitigation strategies.

1. Introduction

In September 2017, Mexico was struck by two powerful earthquakes. The September 7th, M_w8.2 Tehuantepec intraslab earthquake has been the strongest at least in nine decades affecting the southern states of Chiapas and Oaxaca. On September 19th, the M_w7.1 Puebla-Morelos intraslab earthquake, struck Central Mexico approximately 114 km southeast of Mexico City [1, 2]. Damages were concentrated in the States of Puebla, Morelos, Mexico and Mexico City.

These earthquakes caused 477 deaths, 98 and 369 during the September 7th and 19th events, respectively. In Mexico City, 228 fatalities occurred. In the public-school sector, 19,194 school campuses were damaged: 12,014 were reported with minor damages (broken window glasses, for example), 6,970 with moderate and moderate/severe damage, and 210 with damage so severe that required building reconstruction. No casualties were recorded in public school facilities. All prototype school buildings withstood the temblors without collapse.

Only four collapses were recorded in buildings that were either built informally (following self-construction procedures) or that were used as accessory buildings, not for classrooms. According to the Mexican Ministry of Finance, the estimated total damage is US$2.5 billion; rehabilitation (repair and strengthening) and reconstruction in the education infrastructure alone will cost an estimated US$1 billion [3].

The Institute of Engineering at UNAM partnered with the World Bank (WB) and the Mexican National Institute for School Infrastructure (INIFED) to contribute to the reconstruction process through gathering evidences and promoting a broader safer school program countrywide. In this paper, main findings of school performance are presented. Results from ambient vibration are shown. Empirical fragility functions for masonry buildings are presented. The numerical models for most representative buildings are discussed. Detailed results and analyses of this project may be found elsewhere [4].

2. Recovery Plan for School Buildings

In the aftermath of both events, INIFED implemented a Recovery Plan for School Buildings applicable in the 11 most affected Mexican states (i.e. Chiapas, Guerrero, Hidalgo, State of Mexico, Michoacán, Guerrero, Oaxaca, Puebla, Tlaxcala, Veracruz and Mexico City) [5]. Three damage levels were used to classify building damage: minor damage when structural capacity was not affected in a significant way; moderate and moderate/severe damage for repairable damages and very severe damage, for which INIFED opted for building demolition and its substitution with a new prototype facility. Damaged schools in both events (19,194) corresponded to 27.6% of the total exposed; 10.3% of all school campuses had buildings with moderate to very severe damage.

3. Database of School Buildings Damaged in 2017

An electronic information platform for data analysis and school building assessment was developed. Database comprised general information of school campuses, specific information of school buildings, information about external facilities (such as sport facilities, flagpole, civic plaza, etc.), and, when available, photographs and sketches. The information platform included 12,444 building records, i.e. 13.2% of all school campuses damaged and 35.3% of school campuses with moderate to very severe damage, according to INIFED´s damage tagging. It was found that information quality in INIFED´s formats varied widely in consistency and completeness of data.

School buildings were classified according to the construction material (masonry, concrete, steel) and to their corresponding prototype. Prototypes were those that INIFED and its predecessor, CAPFCE, have designed, constructed and regulated over the past 75 years. In Fig. 1, INIFED/CAPFCE building prototypes most often affected by the 2017 earthquakes are shown. When a building did not follow a prototype (either because materials or dimensions were distinctly different) or when different materials were used (like adobe or prefabricated walls), school buildings were classified as "atypical" (46% of all buildings were deemed to be "atypical").

Fig. 1 – INIFED/CAPFCE school buildings prototypes [4]: a) Load-bearing masonry wall buildings -LBMW-, b) One-story concrete frame structure -U1C-, c) Two-story concrete frame structure -U2C-, d) Three-story concrete frame structure -U3C- and e) One-story steel building

Structural and non-structural damage characteristics were included in the database. Structural damage included wall, column, beam, slab, joint and foundation element distress. When available, type and intensity of damage was input. Non-structural damage comprised damage in façade elements, infill walls, finishes, windows, lighting fixtures, water tanks, parapets, fallen objects and fences. When available, distress due to lack of or improper maintenance, such as efflorescence and corrosion, was also registered.

4. Damage Assessment

In general, damage could be attributed to a combination of non-ductile detailing and low seismic strength, substandard construction quality, lack of qualified inspection, inadequate modifications to the structural system and/or lack of proper maintenance.

Masonry structures were found to prevail in Chiapas and Oaxaca, where dispersion of the population through small and distant communities is typical. Reinforced concrete- and steel-moment frame structures were more frequent in the State of Mexico (that surrounds Mexico City) and Mexico City, as they correspond to urban areas [4].

Age of construction is a key parameter for assessing a school structural vulnerability. A comparison of damage level in pre-1985 and post-1985 buildings is presented in Fig. 2. In the case of Mexico, the 1985 Mexico City earthquake represents a point of inflection in earthquake resistant design of structures. In the aftermath of this event, seismic design coefficients were augmented; also, detailing aimed at achieving ductile behavior was implemented [6]. For concrete structures, detailing requirements after 1985 followed the ACI 318-83 [7]. In the case of the 2017 earthquakes, two-thirds of structures in the database were built before 1985. For masonry structures (all with one story), little difference was found in damaged schools built before or after 1985. Conversely, damage frequency and intensity in reinforced concrete (RC) and steel structures was consistently less in buildings built after 1985.

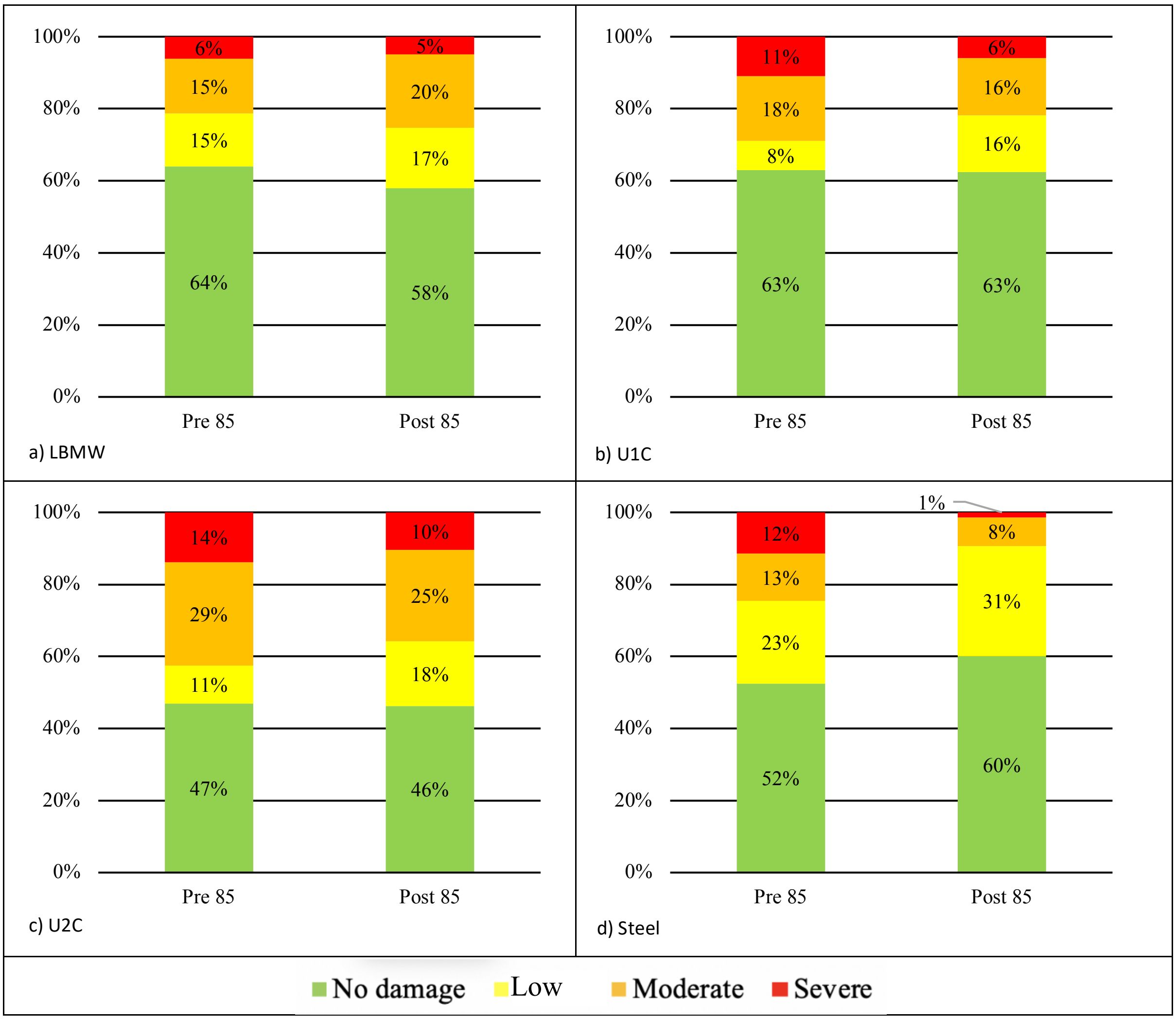

Fig. 2 - Comparison of damage level in pre-1985 and post-1985 prototypes [4]: a) LBMW, b) U1C, c) U2C and d) Steel

Damage distribution of prototype buildings is shown in Fig. 3. Minor damage was exhibited in 75% of buildings in the database. Damage was concentrated in load-bearing walls in masonry structures, and infill walls in RC and steel frame structures. Only 13% and 4% of damaged masonry structures experienced light and severe distress in walls, respectively. Typical damage in masonry walls were inclined cracking and, in few cases, flexural cracking in buttress walls. Post-1985 LBMW prototypes included external buttress walls aimed at increasing lateral shear strength, thus without reducing the available space in classrooms.

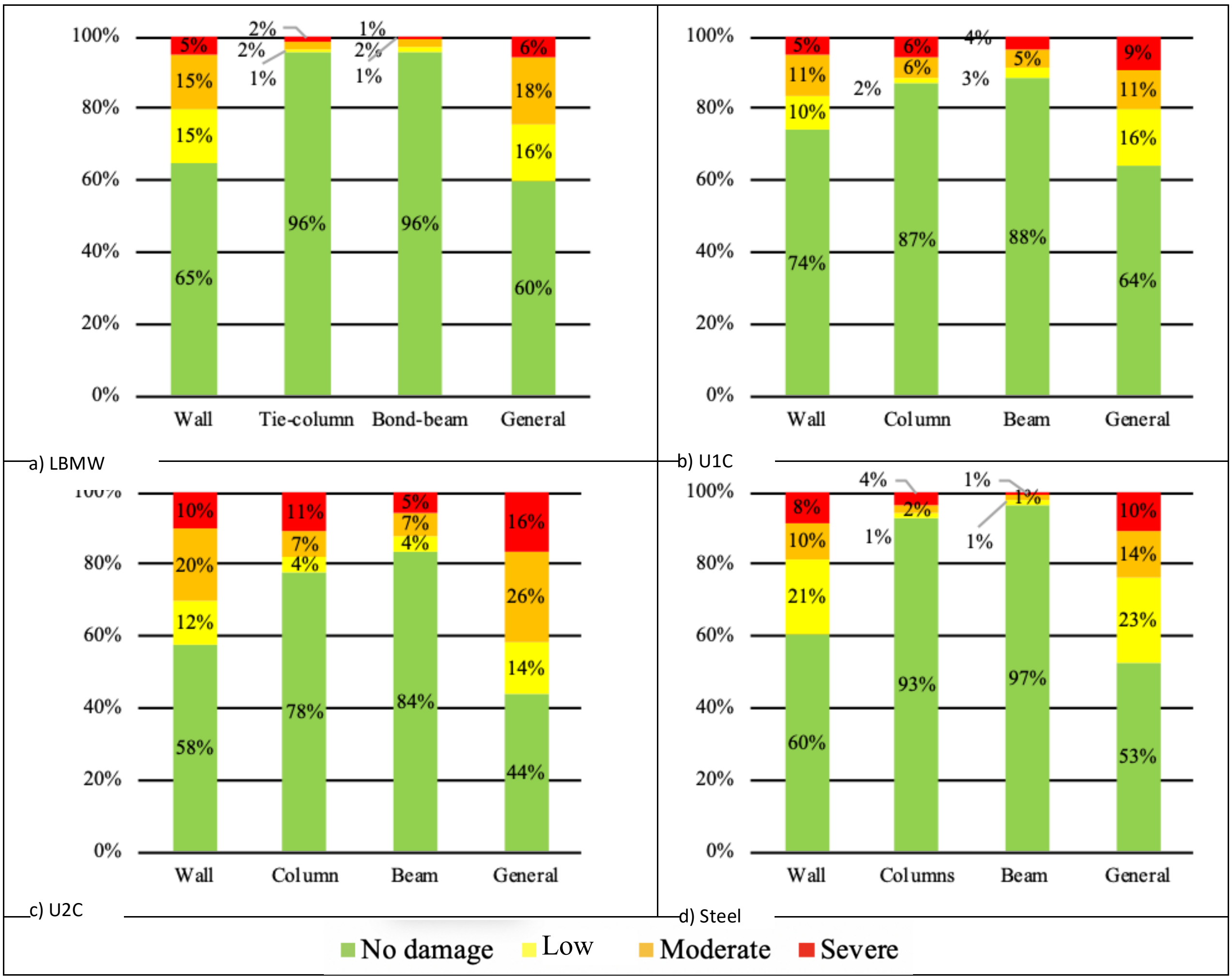

Fig. 3 - Damage level distribution in each prototype [4]: a) LBMW, b) U1C, c) U2C and d) Steel

For concrete structures, most damage was concentrated in columns, especially due to the “short column” effect. Although CAPFCE´s and INIFED´s drawings clearly specified a typical 20-to-25-mm separation between columns and sill walls, existing walls were found to be directly constructed against columns. In pre-1985 structures, column transverse reinforcement was widely spaced (at 300 mm along the column, typically) and was made of stirrups with 90-deg bends at the ends. Beam shear cracking and concrete spalling were seldom observed. In few cases, beam-column joint cracking and spalling were recorded.

Severe damage in steel structures was local buckling of columns steel plates in buildings built in the 1960´s and 1970´s, where a “short column” effect, similar to concrete structures, occurred. Columns were made of cold-formed light-gauge members welded to achieve a complex box-type cross section. Local buckling caused segmental welds to fracture, thus leading to column shortening.

Damage assessment of atypical buildings may be found elsewhere [4].

Following the WB Global Library of School Infrastructure, 11, 13 and five building types were identified for masonry, concrete and steel structures, respectively [4]. Age of construction, span lengths, number of stories and seismic zoning were key parameters for the classification. Three concrete building types were structures that were rehabilitated by adding new concrete walls in the long direction (parallel to corridors) and using infill walls in the short direction as seismic-resisting elements.

5. Dynamic Testing of School Buildings

Ambient vibration testing was aimed at identifying the most significant vibration frequencies for later use in numerical model calibration. Fourteen school buildings were tested under ambient vibrations. Also, in four campuses in Oaxaca, soil dynamic characteristics were measured. Site fundamental periods between 0.63 and 1.25 s were found. Relations between fundamental period, T, vs. number of stories, N, were developed for sites with soft soils and firm soils. For reinforced concrete frames with masonry infills, T= (0.043 to 0.063) N; for masonry structures, T= (0.063 to 0.095) N. Such relations were found to be consistent with those obtained in earlier testing programs [4].

6. Empirical fragility functions

Isoseismal curves for the September 7th and 19th earthquakes were calculated [4]. Correlation between seismic intensities and damage level of registered school buildings was investigated. Masonry buildings, with one to four classrooms, and RC frame structures, of one and two stories were studied.

For masonry structures, as expected, the number of structures damaged and damage intensity diminished as epicentral distance increased [4]. The earthquake intensity (PGA) vs. damage level for the LBMW prototype is shown in Fig. 4. The relation between damage and intensity is not very robust. This could be attributed to the deficient quality and limited quantity of information.

Empirical fragility functions were also developed. Four discrete damage levels (i.e. null, low, moderate, and severe) were used. Functions were calculated for peak ground acceleration (PGA) (Fig. 5) and wall shear stress [4]. In general, trends in empirical fragility functions were consistent with expected behavior: the larger the intensity, the higher the probability of more severe damage.

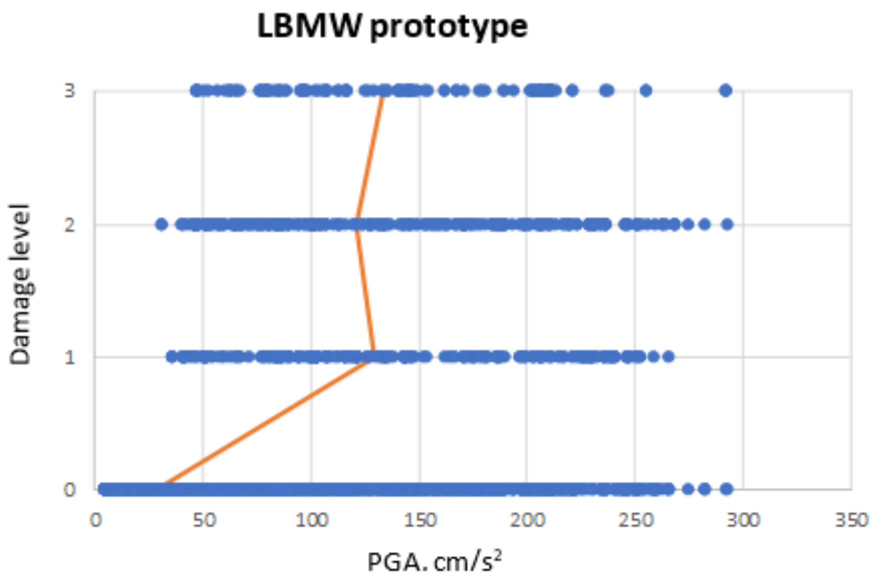

Fig. 4 – Earthquake intensity (PGA) vs. Damage level for LBMW prototype for the September 7th, 2017 earthquake. Damage levels: 0=null, 1=low, 2=moderate and 3=severe. The orange line connects the median of the earthquake intensity at each damage level

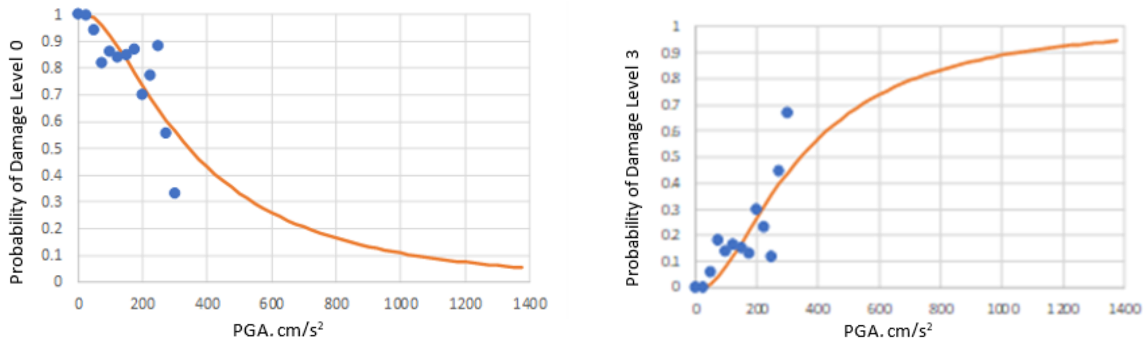

Fig. 5 – Empirical fragility curves obtained from damage distribution maps for damage level 0 and 3, respectively [4]. The orange line is the log-normal function adjusted to empirical data

A similar set of analyses was performed for RC buildings [4]. No correlation between damage frequency and damage intensity with epicentral distance was found. The deficient quality and limited quantity of information are considered as the causes for this lack of correlation. It has been recommended that building information be revised, and that more detailed cost information on repair and reconstruction be gathered.

7. Numerical Modeling of School Buildings

From the 29 building types identified, "index buildings" were selected for further study via numerical modeling. Selected buildings were those that were more frequently affected and that showed distinctly different damage types and intensity. Buildings were also selected to compare pre- and post-1985 designs.

Four masonry index buildings were chosen. These structures had one to four classrooms; all had been designed for Zones C and D with external buttresses. Zones C and D are those with highest seismic hazard according to the Design Manual of Civil Works of the Federal Commission of Electricity (CFE) [8]. This Design Manual is used for seismic design where building codes are not available.

Of the five concrete index buildings, three corresponded to structures designed in 1970 with one, two and three stories (moment resisting frame structures); two were designed in 2011 with one and two stories (moment frames with concrete shear walls). No steel structures were selected to be further analyzed as their damage frequency was much smaller than for masonry and RC buildings.

Linear elastic and nonlinear static analyses were carried out. Material properties, geometry and structural systems were taken from INIFED´s structural drawings. Analysis were made with the help of commercially available software. Modeling assumptions may be found elsewhere [4]. Models were calibrated using the results obtained in the ambient vibration testing.

Design spectra for Zones C and D, and soil types I, II and III (rock, firm and soft soil, respectively) were calculated at specific locations. An importance factor of 1.5, a seismic behavior factor of 2 and an overstrength factor of 2 were used. Elastic spectra calculated from recorded ground motions during the September 2017 earthquakes in Chiapas, Oaxaca and Veracruz were also used to compare against calculated response.

For the nonlinear static analysis, concentrated plasticity models were assumed for beams, columns and walls under flexure, and for walls under shear, following ASCE 41-17 requirements [9]. For masonry walls, a performance-based model was used [10].

Building performance was assessed through the N2 method [11]. Building performance acceptance criteria were consistent with ASCE 41-17. In the case of school buildings, Mexican regulations implicitly expect an Immediate Occupancy (IO) performance level [12]. Story shear – roof displacement capacity curves were calculated and simplified to an elastoplastic curve. Calculated and simplified capacity curves were compared to design spectra in the form of capacity design spectra. To define the IO range, SEAOC´s recommendation was followed [13]; IO range was bounded by the yield displacement and 30% of inelastic displacement capacity.

Comparison of calculated capacity curves and capacity design spectra for one-story masonry index buildings EI1 and EI4 is shown in Fig. 6. Index buildings EI1 and EI4 correspond to one-story LBMW structures with one and four classrooms, respectively. Performance points were defined where the capacity design spectrum intersected the capacity curve. If performance point was located in the elastic branch of the capacity curve, the elastic design spectrum was used. If performance point was located in the plastic branch of the capacity curve, then the design spectra modified to account for inelastic behavior was used. In some cases, the performance point could not be defined as no intersection of the capacity and design spectrum curves was noted in the range studied. These cases indicate a high probability of severe damage and loss of structure´s stability.

Nonlinear static analyses indicate that, for masonry index structures, buildings located in type I soils are likely to attain IO (see Fig. 6). In all other cases, more damage is to be expected. Schools in Zone C in soft soil (type III) and in Zone D, in firm (type II) and soft soils (type III) are likely to exhibit damage that would compromise the structure stability. Such cases should be revised using more refined models. The prototype could be required to be modified accordingly.

Due to space limitations, detailed results for concrete buildings may be found elsewhere [4, 14]. For the case of concrete index buildings, pre-1985 structures could very likely exhibit damage that would compromise its stability under vertical loads. This is consistent with the level of damage recorded after September 2017 events. A continuous seismic risk reduction program for school buildings in Zone C (soil types II and III) and in Zone D (all soil types) should be implemented. In contrast, most index buildings designed in 2011 exhibited a very favorable performance, achieving IO under design spectra demands. School buildings in Zone D, soil III, need to be studied under advanced models to verify their performance.

8. Numerical Assessment of Rehabilitated School Buildings

Most building prototypes rehabilitated after the 2017 earthquakes were masonry structures rehabilitated by means of wall jacketing (i.e. addition of welded wire mesh reinforcement covered with a concrete or mortar layer). In the case of RC frame buildings, infill wall jacketing and addition of concrete walls were the dominant rehabilitation techniques. Steel bracing was only added to one four-story concrete building in Mexico City.

Four index buildings were studied numerically. Two corresponded to one-story masonry buildings, with one and four classrooms (EI1R and E4R, respectively), that were rehabilitated with wall jacketing (Fig. 7). These curves are equivalent to those of Fig. 6, but for numerically-modeled rehabilitated masonry buildings. The other two were one- and two-story RC frame buildings rehabilitated with new concrete walls in the long direction and addition of masonry infills in the short direction [4, 14].

Building performance was assessed through nonlinear static analyses. For the case of wall jacketing, the jacket contribution to strength was calculated following Mexico City´s design requirements [12] and was added to the masonry contribution obtained from the Riahi et al. model [10].

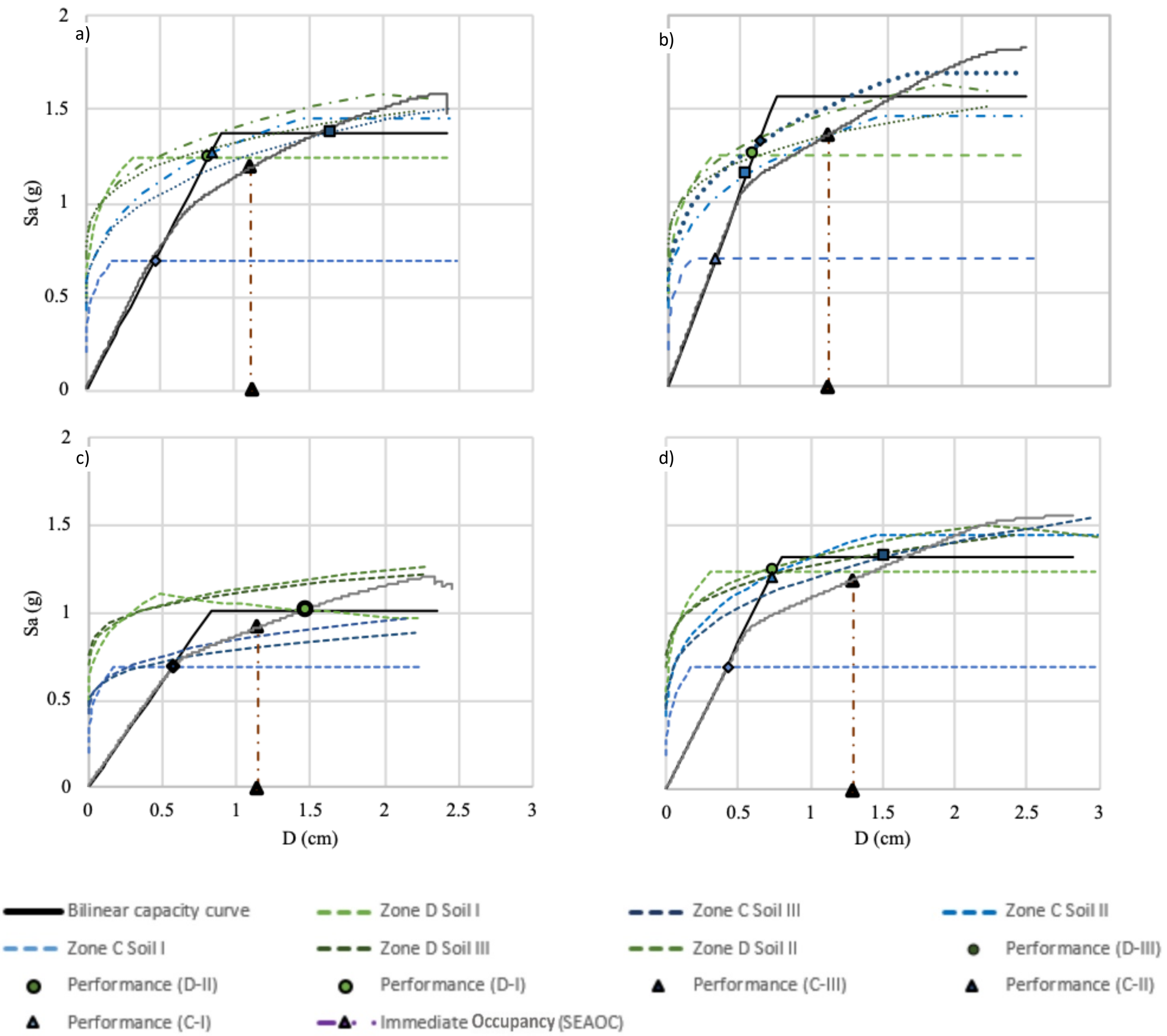

Fig. 6 - Calculated capacity curves, capacity design spectra and performance points for one-story masonry index buildings [14]: EI1 - a) longitudinal and b) transverse direction; and EI4 - c) longitudinal and d) transverse direction) in Zones C and D and soil types I, II and III

Static analyses indicated that under design demands, both masonry and concrete index structures are likely to exhibit larger damage than anticipated for IO. For prototype EI1R, with one classroom, IO is failed to be attained in Zone D, soil types II and III. For EI4R, the critical case was Zone C, soil type III.

Although calculated response does not suggest a significant probability of collapse or severe damage, it is therefore recommended that such cases be revised using more refined models and that, if necessary, structural drawings be modified accordingly.

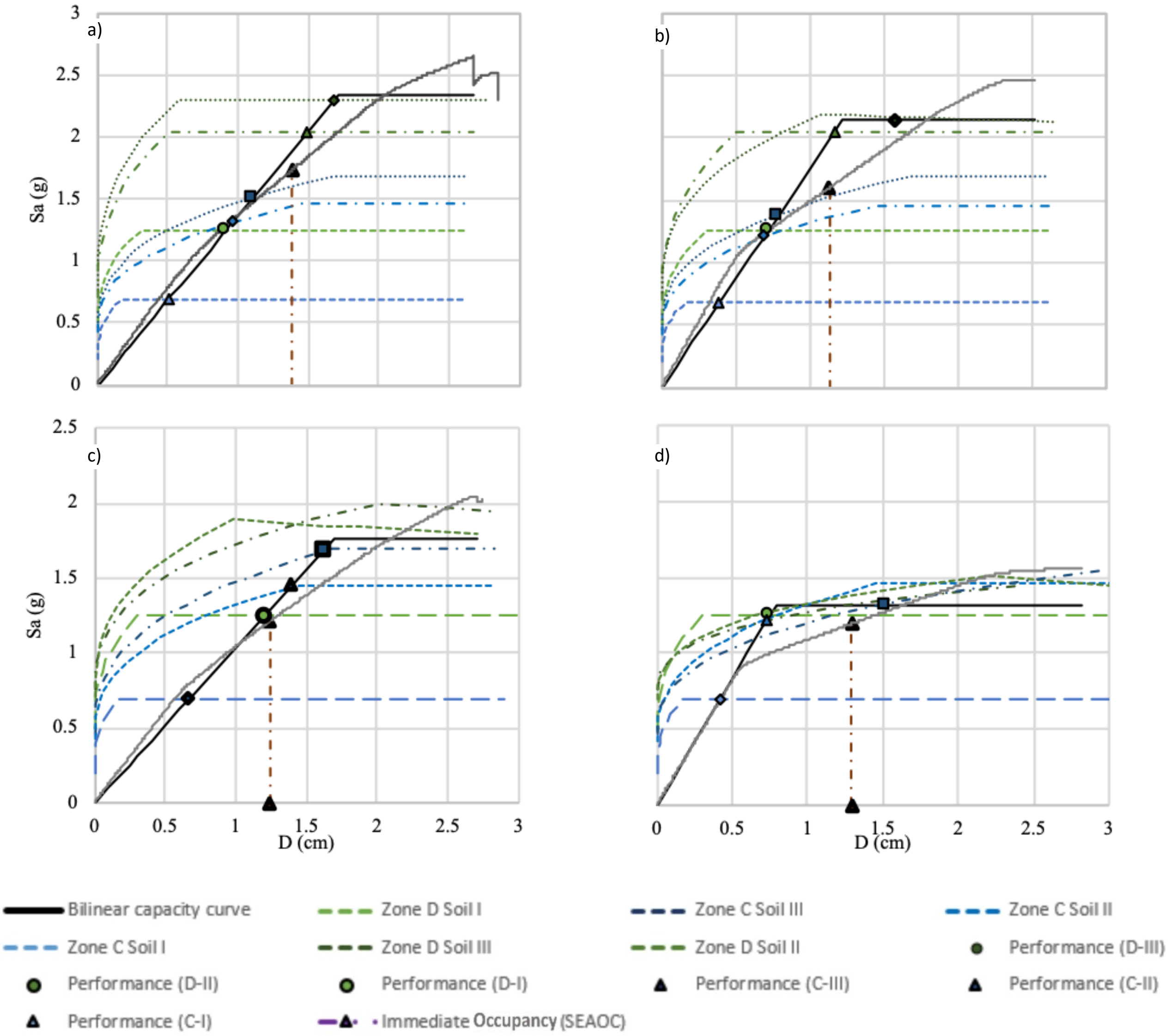

Fig. 7 - Calculated capacity curves, capacity design spectra and performance points for rehabilitated masonry index buildings [14]: EI1R - a) longitudinal and b) transverse direction; and EI4R - c) longitudinal and d) transverse direction) in Zones C and D and soil types I, II and III

9. Conclusions and Recommendations

An analysis of the observed damage in public school buildings in Mexico caused by two major earthquakes in September 2017 was presented. A total of 12,444 buildings in 2,536 campuses were included in the analysis. Buildings are located in nine different states in central and south Mexico, namely: Mexico City, Chiapas, Guerrero, State of Mexico, Michoacán, Morelos, Puebla, Tlaxcala and Veracruz. INIFED reported 19,194 damaged school campuses representing 28% of all campuses exposed to these earthquakes. Common prototype buildings, existing and rehabilitated, were analyzed under linear and nonlinear static procedures. Calculated behavior was consistent with that observed in the field. Compared to seismic design demands, existing structures are likely to exhibit significant damage that could compromise their stability. Rehabilitated structures, conversely, are likely to attain the desired performance level, i.e. immediate occupancy.

Based on observations and data analyses, policy, technical, implementation and sustainability and outreach recommendations aiming at increase schools´ safety and resilience against earthquakes are provided below.

The seismic performance of Mexican schools designed and built with modern regulations, as well as with an adequate maintenance, was superior than that of schools with poor design and/or lack of maintenance. Also, buildings with good construction quality and/or modifications to the structural system, carefully reviewed by engineering specialists, exhibited good behavior.

Based on data gathered and information analyzed, policy, technical, implementation, and sustainability and outreach recommendations are proposed [4]. Such recommendations are considered as areas of opportunity to harness and strengthen INIFED´s and state´s school infrastructure agencies experience and expertise. Evidently, the final aim of the proposals is to minimize school seismic risk, expressed in terms of human, material and functionality losses. A strategy for increasing seismic resistance must consider seismic rehabilitation under modern criteria -design and construction-, as well as a culture of supervised maintenance and sustainable conservation over time.

Related to policy, a multiannual, systematic and integral strategy for incrementally reducing earthquake risk of school buildings is recommended. Aspects related to budget and financing, risk transfer options, project management, enforcement of codes and norms, sustainability over time, INIFED strengthening as a planning and regulating agency, and future developments of school infrastructure should have to be included. A loss-estimation tool, vulnerability/fragility functions and recovery/rehabilitation costs would serve as support. The strategy should focus on pre-1985 masonry and RC school buildings, as well as on atypical school buildings. This strategy should include annual targets, results and efficiency indicators, and monitoring mechanisms. The strategy will be also supported on the information system, methodologies, guides and manuals proposed below.

From a technical perspective, an information system for school buildings with emphasis on seismic risk reduction, with detailed information for each school building, should be developed and be available online. Seismic safety evaluation should be supported on a guide and manual for post-earthquake seismic safety evaluation. Likewise, for school buildings rehabilitation, considerations and requirements for the analysis, design, detailing, construction and inspection of rehabilitation techniques should be included in a guide and a manual. Also, best practices from INIFED, state´s school infrastructure agencies and construction and inspection companies should be assembled in guides for school construction, maintenance and conservation, and for the design, construction, inspection and maintenance of school fences.

The strategy proposed should be implemented via an optimization of seismic risk reduction investments through advanced modeling and refined building assessment. Advanced modeling, coupled with lessons learned, are relevant tools for developing robust financial analyses at the federal and state levels.

To improve the likelihood of success, relevant strategies and actions should be disseminated among education stakeholders: parents, students, school authorities; construction, inspection and maintenance companies; state´s school infrastructure agencies, among others. Higher education institutions, research centers, authorities, civil society organizations at the local and federal level, should be engaged and encouraged to participate through policy and technical recommendations and implementation. A training and certification strategy where new norms, methodologies, guides and manuals are disseminated and transferred, and where specialists, inspectors, technicians, etc. are certified is recommended.

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