International Journal of GEOMATE, June, 2020, Vol.18, Issue 70, pp. 74 - 80
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.70.9240
Geotechnique, Construction Materials and Environment

RESILIENCY OF A FOUR-STOREY STANDARD SCHOOL BUILDING USING THE REDI FRAMEWORK

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*Corresponding Author, Received: 01 Oct. 2019, Revised: 02 Nov. 2019, Accepted: 01 Dec. 2019

ABSTRACT: Public school buildings in the Philippines are built with a code-based design philosophy, wherein the life safety of the occupants is the sole performance objective. While the loss of life is the primary consideration for design, other losses such as cost of repair or replacement and service losses are to be expected after an earthquake. The 2017 Surigao Earthquake damaged 47 schools and caused a 10-day suspension of classes. Three years after the 2013 Bohol Earthquake, 279 classrooms from 696 schools are still under construction. A resilience-based design philosophy takes into consideration safety and other losses including recovery. To assess the resilience of a structure, a resilience-based seismic assessment methodology was adopted after the REDi Framework. Other tools utilized for the seismic assessment were the FEMA P-58, their accompanying software PACT, as well as SeismoStruct. It consists of the identification of losses in terms of cost and time, as well as the evaluation of proper building management and design practices. As a pilot study, a four-storey twelve-classroom template was assessed for seismic resilience. Numerical simulations and analysis showed that the structure was not resilient in ambient and building resilience.

Keywords: Resilient buildings, Resilience-based design, PACT, Loss assessment, REDi rating

1. INTRODUCTION

The Philippines is a seismically active country due to its location along the Ring of Fire, otherwise known as the Circum-Pacific belt. This Circum-Pacific belt is a 40,000-kilometer-long zone of earthquakes, volcanic eruptions, and plate boundaries where the majority of the world's earthquakes occur [1]. Due to the frequency of earthquake occurrence within the Ring of Fire, structures in these countries must be built to withstand seismic activity. In Metro Manila, the looming threat of a high-magnitude earthquake named "The Big One" prompts the revisiting of seismic resistance of essential structures, most especially public school buildings, in the country. These public schools serve a dual purpose: the first and primary cause of operation is as centers of education for Filipino children and the second is as evacuation facilities during times of disaster [2].

In the event of an earthquake, the damaging or collapse of the school building will put the lives of youth at risk of injury or loss of life. Similarly, a collapsed school building will not be able to serve its second purpose as temporary shelters for victims of the disasters. Past instances wherein school buildings were affected by seismic activity include the 2013 earthquake located in Bohol wherein 696 schools were either damaged or destroyed and a student population of 270,000 individuals was affected [3].

Public school buildings in the Philippines follow the design philosophy of code-based design, wherein they are designed based on the National Structural Code of the Philippines (NSCP). Adapting this design philosophy ensures that structures are life-safe when a certain magnitude earthquake occurs, though it does not ensure that the building suffers no damage nor will it remain operational after the seismic event, as per Section 208.1.1 of the NSCP [4]. The performance of a school after an earthquake is an essential aspect in its operation, and total collapse will render it unusable for an extended period. The Bohol Earthquake rendered 279 classrooms inoperational three years after the event [5].

Seismic resilience is defined as the ability of an organization or a community to recover from an earthquake [6]. The existing and prevalent design philosophy is the code-based design, which addresses the loss of life after an earthquake but fails to consider structural damage. Resilience-based design (RBD) takes additional factors into consideration to improve the seismic performance of a building. A key component in RBD assessment is the minimization of structural and non-structural damage during an earthquake. Such damage minimization increases occupant confidence in the structure as there is a level of unpredictability on the performance of the building as it reaches its limits. Additionally, the goal of a prompt recovery after the occurrence of a disaster is greatly emphasized in the RBD philosophy. This parameter can be measured using the investigation of both the building performance and the building environment after the earthquake.

Table 1 REDi Baseline Resilience Objectives for Different Resilience Rating

Rating	Re-occupancy	Functional recovery	Direct financial loss	Occupant safety
Platinum	Immediate	< 72 h	< 2.5%	Injuries Unlikely
Gold	Immediate	< 1 month	< 5%	Injuries Unlikely
Silver	< 6 months	< 6 months	< 10%	Injuries Possible

The REDi Rating System was developed by Arup to measure the level of resiliency of a structure by assigning a certain resilience rating, namely silver, gold, and platinum. Each resilience rating has certain criteria that a building needs to achieve under three resilient design and planning categories: organizational resilience, building resilience, and ambient resilience. Organizational resilience includes the assessment of factors beyond the structure itself, such as emergency evacuation systems and procedures and plans for utility disruption. Building resilience quantifies the performance of the building components during an earthquake event. Ambient resilience considers the environmental factors and other facilities that may impact the building in consideration. The final method of quantification is the criteria under evaluation, in the form of a loss assessment. This is done to determine the financial losses and the downtime of the structure in the event of an earthquake.

The resilience objectives for loss assessment can be seen in Table 1. Once all the criteria are met, the building qualifies for a resilience rating [7].

This study aimed to create a concrete resilience methodology and perform an RBD assessment on a four-storey twelve-classroom standard school building located in Manila, as seen in Fig. 1.

Fig. 1 Four-storey standard school perspective.

2. METHODOLOGY

The following procedure was conducted to determine the resiliency of the four-storey school building.

2.1 Checklist And Site Visit

The REDi Rating System was made as the basis for the creation of a checklist to determine the seismic resilience of the structure. The criteria taken under consideration to be adapted in the checklist were the silver-required, gold-required, and the platinum-required criteria from the REDi Framework. Within the checklist are the four resilience categories explained beforehand, namely: building resilience, ambient resilience, organizational resilience, and loss assessment. A site investigation was conducted in conjunction with an interview with the head of disaster and risk management at the school in order to assess organizational and ambient resilience.

2.2 Direct Financial Loss Assessment

To assess compliance with building resilience and the baseline resilience objectives, a loss assessment was conducted. This was done to assess whether the building will minimize injuries, repair costs, and repair times at the scenario expected earthquake. The seismic assessment of the building follows the procedure listed in FEMA P-58 [8] procedure. The procedure comes with the accompanying software, the Performance Assessment Calculation Tool, or PACT, which can be used to estimate the earthquake losses.

First, basic building information was inputted into PACT. These include the number of stories, the total replacement cost, the core and shell replacement cost, the replacement time, floor areas per floor, and the max number of workers per square foot. The replacement cost was determined to be Php 46,497,225; based on the project cost plus an assumed 25% for demolition costs. The replacement time was estimated to be 240 days.

Second, the population of the building was modeled. The type of occupancy and population distribution per floor was inputted. The default daily distribution was changed to reflect the schedule of Philippine public schools which have two shifts.

Third, the component fragilities to be used in the structure were inputted. A component fragility describes the susceptibility of a component to damage using different damage state fragility functions. For example, a masonry wall could have two damage states; the first being the first occurrence of cracks, and the second being wide diagonal cracks signifying shear failure. Each damage state corresponds to their respective consequence functions, converting the damage

Table 2 Checklist for Organizational Resilience

Criteria	Rating	Remarks
Back-up for Utility Lines	Gold	Water: 2 water tanks Power: Emergency lights
Security	Platinum	No security systems needing power Gates are locked during earthquake to avoid stampeding of parents
Post-Earthquake Inspection	Platinum	Inspectors from city hall ready to mobilize a day after earthquakes occur
Long-lead Time Items	Platinum	No identifiable long-lead time items
Food and Water	Silver	Food and water available only for one day

Table 3 Checklist for Ambient Resilience

Criteria	Rating	Remarks
Design for Liquefaction	Not resilient	Liquefaction is likely to occur according to hazard maps Building was not designed for liquefaction
Other Ground Failures	Platinum	Building not susceptible to other ground failures such as landslides
High Tsunami Hazard	Platinum	Five-meter inundation depth Ground floor not above inundation depth
High Hazard from Surrounding Buildings	Platinum	Buildings around have no structural deficiencies
Assessment of Surrounding Non-building Structures	Platinum	No major non-building structures pose a risk to the building

states into losses in terms of cost, time, injuries and fatalities. PACT provides predefined component fragilities, so the most appropriate were selected for the structure. PACT did not have component fragilities for stairs, so the researchers developed one (Fig. 2) using incremental dynamic analysis (IDA) of a 3D stair model.

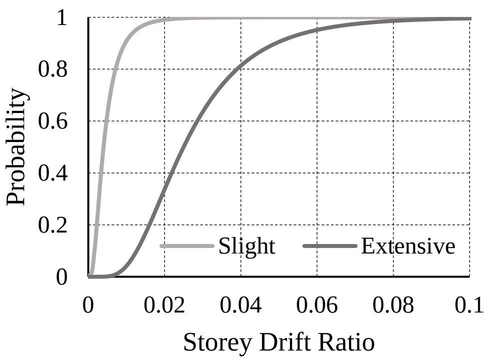

Fig. 2 User-defined stair fragility

Additionally, the consequence functions provided were based on American repair practices. Hence, consequence functions appropriate to the Philippine settings were developed with the help of two experts in seismic repair and retrofitting in the Philippines and applied these functions to the selected component fragilities.

Fourth, the performance groups were specified. Performance groups are the components of the building per floor that are subject to the same earthquake demands such as story drift and floor acceleration. They can be directional or non-directional. The number of components per performance group was specified.

Fifth, structural analysis was conducted using the procedure for Non-Linear Intensity-Based Assessment as per FEMA P-58. Through this procedure, the collapse fragility of the structure was determined. The distribution of demands such as peak story drift and peak floor acceleration was also determined.

2.2.1 Collapse fragility and demand distribution

The design level earthquake (DLE) was the level of intensity chosen, as specified by the REDi Rating System. The target spectrum was obtained using the Philippine Earthquake Manual [9], which

Table 4 Checklist for Building Resilience

Criteria	Rating	Remarks
Code Minimum Requirements	Not resilient	Failed in code-based drift check
Minimize Structural Damage	Platinum	Average damage states of beam-column joints in PACT simulation is less than 1% at all levels
Minimize Non-Structural Damage	Platinum	Non-structural components did not contribute to significant losses
Protect Facades	Silver	Masonry walls had damage state greater than 1 at all levels Many masonry walls experienced shear failure
Anchor Heavy Building Contents	Platinum	No major heavy contents to be in the building
Other Building Contents	Platinum	No critical, priceless or expensive building contents
Stairs	Platinum	Average damage state of first floor is less than 1

contains a collection of seismic hazard maps.

The structure was modeled in the Building Modeler facility of SeismoStruct [10]. An inelastic frame element with plastic hinges was used for the columns and beams. An Eigenvalue Analysis was used to determine the fundamental period of the structure.

Then, the project was setup for IDA. Acceptance criteria based on ASCE 41-13 were used for the performance criteria of the structure. FEMA 695 [11] named 22 far-field earthquakes records to be used. PEER NGA West [12] provided 21 earthquake records scaled to the fundamental period of the building. The IDA started from a small load factor and incremented until the onset of numerical instability. Nodal displacements per time step per load factor per earthquake record were obtained from SeismoBatch. The maximum drift ratio per load factor per earthquake was calculated. A load factor is representative of a scaled Sa(T) by the load factor.

FEMA Hazus MR2.1 [13] provided drift ratios indicative of structural damage states. The mean of the lognormal cumulative distribution was obtained from the average of the natural logarithm of the Sa(T) at the drift ratio threshold of the 21 records. The standard deviation was obtained from the natural logarithm of the Sa(T) at the drift ratio threshold of the 21 records.

Figure 3 shows the derived collapse fragility curve of the structure. The computed median collapse is 2.742g and the computed dispersion is 0.401. FEMA P-58 suggests using a dispersion of 0.6 to account for other uncertainties.

The distribution of demands is computed by PACT based on the peak demands from several time histories. These peak demands were derived from the results of the IDA at the load factor of 1. This data is input into PACT.

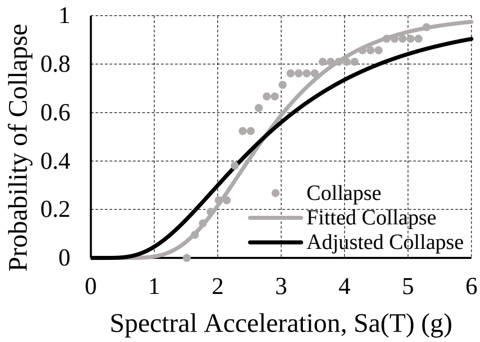

Fig. 3 Collapse fragility of the structure

Finally, PACT calculates the probability distributions of repair cost, repair time, injuries and fatalities. The median loss is the scenario expected loss, with the exception of the median repair time, as it needs further modification using the REDi Modified Downtime Methodology.

2.3 Downtime Assessment

First, repair times and damage states were extracted from the analysis from PACT. Repair classes for each component were assigned based on the average damage state. Repair classes for structural and non-structural components for each corresponding damage state were provided by the Framework. A desired probability of non-exceedance was selected. The median probability of non-exceedance was advised.

Downtime due to repairs was considered. The number of workers was computed based on building area and damage units corresponding to the repair sequence. Repair time at each floor was then computed based on the worker days required for each repair sequence at each floor and the number of workers. A repair schedule that considered the series of work according to floor and number of workers was made.

Downtime due to delays was considered. Impeding curves, median and dispersion values of delay based on building characteristics were provided by the Framework. The probability of non-exceedance was used in determining the delay times.

Downtime due to utility disruption was considered. Utility disruption curves for electrical, water, and natural gas systems were provided by the Framework. The probability of non-exceedance was used in determining the delay times. Delays due to natural gas and water system disruption were based on repair rate. Repair rate was calculated based on the peak ground velocity.

The prominent delay of post-earthquake expected losses. The final output was the rating of the structure as either platinum, gold, silver or not resilient. In order for the building to be considered as seismically resilient, it should be able to fulfill all of the silver-required criteria. If all silver-required criteria were met, then the next resilience tier is taken into consideration. If it did not fulfill even one of the silver-required criteria, it was not considered to be resilient.

3. DATA AND ANALYSIS

The probability of non-exceedance of the repair cost, against the repair cost, is presented in Fig.4. The abscissa presents the probability at which the total repair cost is less than or equal to the total replacement cost of the structure at total collapse. The median value of repair cost is taken to be equal to PHP 1,203,416.15. This puts the direct financial loss at 3%.

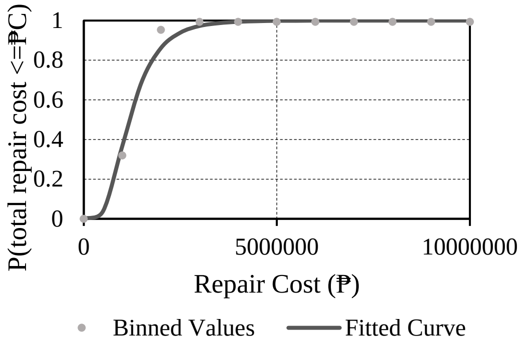

Fig. 4 PACT repair cost

The median values for repair cost indicate that the structure is resilient in terms of direct financial loss. It is important to note that numerous non-structural components were neglected such as doors and windows as PACT did not provide their component fragilities, and development of component fragilities is outside the scope of this study. Hence, the obtained median repair cost may be an underestimation of the true scenario expected loss.

In Fig. 5, the probability distributions of injuries and fatalities are presented. The plots both provide a median value of 0.

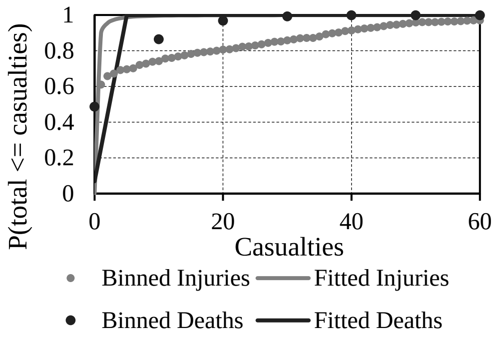

Fig. 5 Casualties

These results are consistent with the expectations of the researchers. The obtained DLE had a value of 0.511 g at a fundamental period of 0.629 seconds, which is far lower than the median of the collapse fragility at 2.742 g. This shows that it is probably very unlikely that collapse occurs.

Figure 6 illustrates the re-occupancy repair sequence of the structure. The structural repair sequence is first considered before other sequences. The interior and stair sequence occur simultaneously. The per floor sequences occur consecutively. Using modified repair time, the total delay due to repairs is 53.510 days.

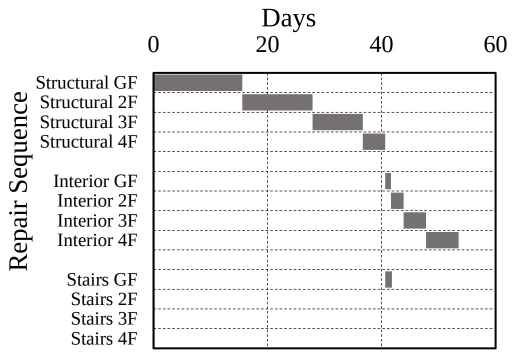

Fig. 6 Modified repair time for Re-occupancy

Figure 7 shows the Functional Recovery Timeline of the building. All components to be repaired was of repair class 3 and 2. It would take

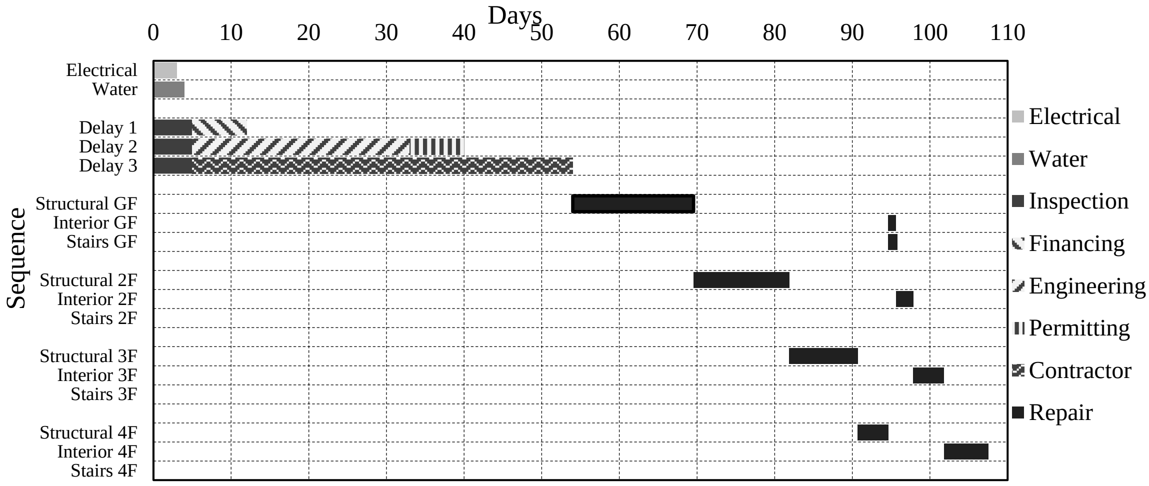

Fig. 7 Functional recovery time

Table 5 Checklist for Baseline REDi Objectives

Baseline Resilience Objective	Value	Rating
Downtime	Re-occupancy = 108 days Full Recovery = 109 days	Silver
Direct Financial Loss	Scenario Expected Loss = 3%	Gold
Occupant Safety	Expected Injuries = 0 Expected Fatalities = 0	Gold

107.510 days for the Functional Recovery and Re-occupancy of the structure. Functional Recovery and Re-occupancy are the same because there are no components that achieved a repair class of 2 and the utility disruption was less prominent than the delays. Full Recovery takes 108.584 days. Full Recovery only differs in the minor repair to the ground floor beam-column joints. The structural repair mostly consists of major repairs to masonry walls.

The median values for Re-occupancy and Functional Recovery of almost three months indicate that the structure is resilient in terms of recovery.

From Table 2, it can be concluded that the school building has an overall silver rating for organizational resilience.

From Table 3, it can be concluded that the school building is not resilient in ambient resilience due to the structure not being designed for liquefaction despite it being in a high liquefaction potential zone.

It can be seen in Table 4 that the building is not resilient in building resilience due to failing drift requirements of the structural code.

Table 5 presents the compliance of the structure with respect to the baseline REDi objectives. Despite of the structure meeting these objectives, it failed to meet requirement of ambient resilience and building resilience.

4. CONCLUSION

Structures, if designed properly based on existing codes, can escape structure collapse during seismic events. However, functions of structures are often disrupted during seismic events as repairs of damages entail time and costs. A new design paradigm – Resiliency-based design addresses, not only the safety requirement but also the level of damage and the time it will take to repair the damages to bring the structure back to perform its intended function. REDi framework provided a rating for structure depending on its compliance with building, ambient, and organizational resilience.

This study assessed a standard four-storey twelve-classroom standard school building and has concluded that the building is not resilient based on the REDi Framework as it failed to achieve a rating in ambient and building resilience.

5. ACKNOWLEDGMENTS

The researchers wish to acknowledge Seismosoft for sharing a student license of their software, SeismoStruct.

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