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Increasing safety in residential construction through a simplified earthquake- and typhoon-resistant guidelines

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A B S T R A C T

This paper presents the engineering basis for a document, Residential Design and Construction Guidelines (hereafter, Guidelines). The Guidelines is developed by the engineers of Build Change and its partners based on their technical reconnaissance after the 2013 earthquake in Bohol on October 15, 2013, and Typhoon Haiyan on November 8, 2013. The Guidelines are centered on the observations of typical residential construction and damage in these areas and the requirements of the 2010 National Structural Code of the Philippines. The Guidelines provide illustrated and simple instructions on residential construction, making them accessible to homeowners and local builders. The Guidelines are designed for disaster-resistant, permanent low-rise housing construction, endorsed by the Department of Public Works and Highways of the Philippines (in March 2016). Increasing understanding and application of the Guidelines in residential construction in earthquake- and typhoon-prone areas will increase the structural safety of houses and the country's resiliency.

1. Introduction

The Philippines is vulnerable to two natural hazards, typhoons and earthquakes, due to its geographical location (Yumul et al., 2011). The M7.1 Central Visayas earthquake hit near the city of Catigbian, on Bohol Island in the Philippines, on October 15, 2013 (Build Change, 2014). The earthquake damaged over 73,000 buildings, with 14,512 houses considered completely destroyed and 58,490 partially damaged. Closely following the Bohol earthquake, Typhoon Haiyan hit several islands in the Philippines on November 8, 2013. It was estimated that over 1.1 million houses were damaged by the typhoon, displacing around 3.62 million people at the peak. It has been determined that non-compliance with building codes, thus, producing informal construction, is a major cause of disaster vulnerability in housing (Usamah et al., 2014).

The current literature focuses on designing systems of disaster resilience through disaster management (Charlesworth & Fien, 2022; Shaikh et al., 2022) and investigating housing construction practices in the informal housing sector (Chmutina & Rose, 2018). However, there is a lack of information on two important factors in building resilient housing: detailed observations of causes of damage to residential buildings; and a detailed structural calculation addressing every issue identified as a cause of damage to residential buildings.

Furthermore, the present literature suggests that building local capacities is critical to community resilience (Leeman et al., 2017). The gap between knowledge and its application is a well-known gap that challenges capacity-building (Brownson et al., 2018). The Residential Design and Construction Guidelines, developed by the engineers of Build Change and its partners based on their technical reconnaissance of damaged houses, provide illustrations and simple step-by-step instructions for the process of design, planning, and construction of an earthquake- and typhoon-resistant house, making them accessible not only to construction professionals but also to homeowners and local builders. It is hoped that applying the Guidelines in residential construction in earthquake- and typhoon-prone areas will increase the structural safety of houses and the community's resiliency.

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2. Background

2.1 Common Types of Residential Construction

Two of the most common types of residential construction in the areas affected by the Bohol earthquake and Typhoon Yolanda are one- to two-story timber frames with either non-structural infill panels made from woven grasses, known as amakan or heavier timber planks and one- or two-story hollow concrete block masonry wall buildings with reinforced concrete foundations and often with beams and columns acting as confining members. Floor framing for the upper floors and roofs is generally of wood, although occasionally, concrete slabs are used in the masonry wall buildings. Some construction combines timber and masonry framing: such as a single-story masonry wall topped by timber framing or masonry walls combined with timber columns and beams. For masonry and timber construction typologies, recurring defects were identified through observations, as enumerated in the following sections.

2.2 Key Sources of Failure

2.2.1 Configuration

Many of the houses observed, both masonry and timber, had vertical and horizontal irregularities such as cantilevered terraces, soft stories, and re-entrant corners. Typical masonry residential construction had unconfined and unbraced masonry gable walls, large openings in walls, and unconfined courses of masonry above openings, which were observed to collapse out of plane frequently. Both timber and masonry homes had insufficient shear wall area to resist typhoon- and earthquake-level lateral forces, causing them to fail in-plane.

2.2.2 Connections

Most of the masonry houses had structural elements with very weak connections, including insufficient lap splice lengths, development lengths, and the absence of seismic hooks. Purlin-to-truss and roof-to-top plate connections were insufficiently strong, resulting in roof failures in both timber and masonry-walled houses, particularly under typhoon-level wind loads. In houses with raised wood floors, racking of the entire house was observed as the result of a lack of floor-to-wall ties. Foundations were often lacking or, where present, were too shallow for proper anchorage against overturning and sliding.

2.2.3 Construction and Materials Quality

In the Philippines, builders are typically compensated for accomplishment rather than the quality of construction. Poor construction quality contributed to structural failures in residential construction, where weak hollow concrete blocks and a lack of properly grouted joints contributed to the failure of the wall. In general, it was apparent that both homeowners and builders have little appreciation for the importance of construction and material quality to the resilience of a building in a disaster. Using cheaper and poor-quality materials also contributes to a lack of resiliency in timber house construction. While coco lumber is widely used due to its easy availability and low cost, its strength and durability are generally low and inconsistent.

3. Design criteria

The design criteria for the Guidelines were developed with the intent to apply to the majority of low-rise housing conditions in the Philippines, independent of location and taking into account the most likely governing earthquake and typhoon-related wind loads, with a few exceptions where certain common typologies were structurally sound and economical in regions of lower wind speeds. The criteria are based on values for building materials properties and construction methods commonly used per testing and field observations. The following design criteria were employed in the development of the Guidelines.

3.1 Codes Referenced and Engineering Inputs

All designs and criteria were based on the requirements of the 2010 National Structural Code of the Philippines (NSCP), 6th Edition, 4th Printing. Wind design was based on NSCP Section 207, where buildings were considered located in Wind Zone I, with a Basic Wind Speed of 250 kph (155 mph) and an Importance Factor of 1.0. It was determined that Post and Beam construction could only reasonably meet design criteria in Wind Zone III areas. In Wind Zones I and II, it is not practical to design Post and Beam construction for code-level forces utilizing readily available material sizes and construction methods. This guidance is provided on post and beam construction with a clear caveat that it is only appropriate in the regions enumerated in the Guidelines. Additional wind design considerations are a typical roof slope of 30°, Surface Roughness C; Exposure Category C, and both masonry and timber houses considered as Enclosed structures. For seismic considerations, NSCP Section 208 governed design considerations. Structures were conservatively assumed to be located in the most Seismic Zone 4, with Seismic Zone Factor $Z = 0.40$, and Seismic Importance Factors, I and Ip, equal to 1.0. The Soil

Type is D with a Seismic Source Distance of greater than 15 km. Consequently, its near source Factor, Na, is equal to 1.0, and Near-source Factor, Nv, is equal to 1.0. The assumed Response Modification, R, and Overstrength, O0, factors are found in Tables 208-11C and 208-11D of the NSCP. A summary is found in Table 1.

Table 1

Response Modification, R, and Overstrength, O_0, Factors

Building Type	R	O_0
Masonry Bearing/ Shear Wall	4.5	2.8
Timber Shear Wall	5.5	2.8
Timber with Metal Strap Bracing	2.8	2.2

3.2 Materials Strength Assumptions

Material strength assumptions were not solely based on the provisions of the NSCP. Consideration was also given to the type and quality of materials available and typically used in the affected areas based on the reconnaissance findings. Reinforcing steel was set to minimum strength, fy = 276 MPa (40 ksi), and both minimum 29 gauge metal decks and 18-gauge (1.2mm or 0.048") metal strapping were assumed to have fy = 228 MPa (33 ksi). The minimum compressive strength of concrete assumed is f'c = 17 MPa (2500 psi), under NSCP 401.2.1. This can be achieved with a concrete mix ratio of 1:2:3 (parts cement/sand/coarse aggregate), which is widely used in the Philippines. The minimum compressive strength of masonry, f'm = 4 MPa (580 psi), was used, as specified in NSCP 705.3.1, with Modulus of Elasticity of concrete masonry, Em, = 750f'm, = 3000 MPa, in accordance with NSCP equation 706-4. The minimum compressive strength of grout is asspecified in NSCP 703.4.1, f'g = 15.0 MPa. Nominal shear unit capacities for both wood-framed shear walls and wood-framed plywood shear walls were taken from Table 4.3C and Table A.4.3A respectively of ANSI/AF&PA SDPWS-2005, as these values are not provided in the NSCP. General timber properties were taken from the Table 603.2-1 in the NSCP for commonly used construction lumber. The types of timber and capacities assumed for the design criteria are shown on Table 2.

Table 2

Properties of timber

Species	Bending and tension parallel to grain (MPa)	Modulus of elasticity (GPa)	Compression parallel to grain (MPa)	Compression perpendicular to grain (MPa)	Shear parallel to grain (MPa)	Strength classification
Gmelina (Yemane), 80% Stress Grade	12.6	4.09	7.87	3.40	1.96	Moderately low
Lawaan (Lauan), 80% Stress Grade	13.9	5.83	8.18	1.72	1.48	Medium
Mahogany, 80% Stress Grade	16.5	4.66	10.5	3.83	2.71	Moderately high

Allowable loads in seasoned wood for common wire nails were taken from Table 619.3-1 of the NSCP to determine the required nailing of each wood component.

4. Implications on applications

4.1 Building Dimensions and Configuration

Based on the reconnaissance findings, limitations were placed on the type of buildings the Guidelines would address. Calculations were developed for both one- and two-story confined masonry and wood-framed houses to be constructed in the Philippines. A building footprint of 49 m^2 (7 meters in either direction) or less was chosen to limit the house size to be considered. These dimensions reflect what is typical of most single-family residential construction in the Philippines and the advisable limits on horizontal configurations for the construction typologies and loads considered. For calculation purposes, lateral and vertical load-resisting wall spacing is assumed at a maximum of 3.5 meters on center in all directions. Story heights are assumed to be 2.75 meters maximum. Where sloped timber-framed roofs occur, the roof is assumed to have a 30-degree slope, resulting in a maximum roof height above the top of a wall of an additional 1 meter.

4.1.1 Confined Masonry Buildings

Four general building configurations are considered in the calculations for confined masonry houses: two-story with a heavy (concrete slab) roof, two-story with a lightweight (wood framed) roof, one-story with a heavy roof, and one-story with a lightweight roof. For design calculations, the configuration that would result in the controlling demand-to-capacity ratio was considered for each case.

4.1.2 Timber Buildings

Two configurations of timber homes were considered: one-story timber walls with a lightweight roof, and two-story timber walls with a lightweight floor and roof.

4.2 Building Systems Included in the Guidelines

4.2.1 Confined Masonry

Foundations consist of reinforced concrete strip footings embedded below grade with a reinforced masonry foundation wall that extends to the ground floor level and is topped by a reinforced concrete plinth beam at the ground floor level. Walls are confined masonry, grouted cells with vertical reinforcing and horizontal reinforcing distributed in the bed joints. Walls are constructed before the vertical and upper confining elements are cast. The walls are vertical load-bearing and the primary lateral force-resisting elements for the building. Reinforced concrete vertical confining elements are located at wall ends, intersections, and full-height openings to confine the masonry walls adequately. Additional wall reinforcing is provided for confinement around window openings. Window and door openings extend to the underside of the ring beam above, which acts as a lintel to support vertical loads above. An upper horizontal reinforced concrete ring beam is placed at the top of the wall. Where the walls meet a lightweight roof above, the ring beam acts to brace the top of the wall out-of-plane and distribute the load to the perpendicular walls, so the lightweight roof is not required to function as a diaphragm. Suspended slabs consist of solid reinforced concrete 15 cm thick. All of these assumptions are detailed in the Guidelines as recommendations.

4.2.2 Timber Framed

Foundations consist of reinforced concrete strip footings embedded below grade with a reinforced masonry foundation and knee wall that extends a maximum of 1 meter above grade. The knee wall is topped reinforced concrete cap beam. Walls are framed with timber studs and the bottom plate is securely anchored to the top of the cap beam below. A double-top plate is used at the top of the wall. The wall studs resist the gravity forces in the building from upper levels or the roof. The walls are covered for lateral bracing by plywood sheets, diagonal timber plank sheathing, or metal X-bracing to create shear walls. Sistered studs or posts are provided at the ends of shear wall segments to resist overturning and anchored to the cap beam below with metal straps. The studs span between the bottom and top plates to resist out-of-plane loads. The top plate spans between perpendicular walls so that the timber-framed floors and roof do not need to act as a diaphragm. Floors are supported on timber joists that span between and are supported on stud walls topped by double plates. All of these assumptions are detailed in the Guidelines as recommendations.

4.2.3 Lightweight Roofs

Roofs are framed with either timber rafters and ties, or timber trusses with plywood gusset plate connections, depending on the roof span. Purlins are positively connected, perpendicular to the slope of the roof, with wood blocks or Typhoon-resistant metal straps easily fabricated from locally available metal sheets. Rafters or trusses are positively connected with similar metal straps to the wall top plates to resist uplift. Light gage corrugated metal sheeting is nailed to the purlins and to all edge members.

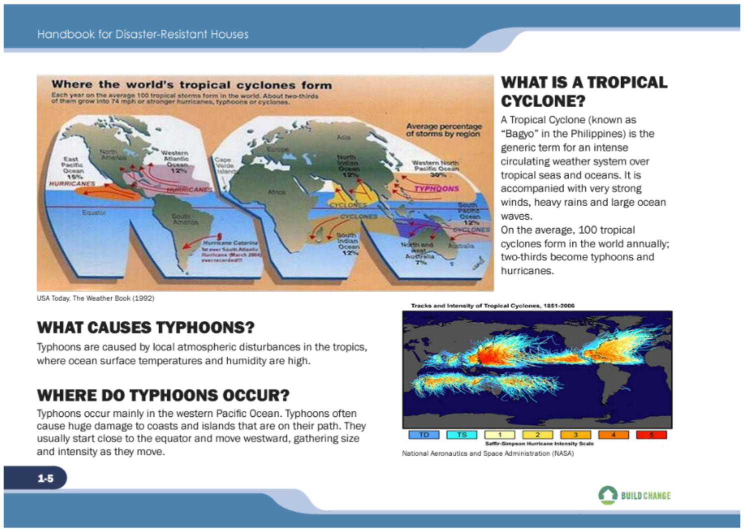
5. Residential design and construction guidelines contents

5.1 Organization

The Guidelines are prepared using easy-to-understand language, simplified sketches and graphics, and photographs of actual construction as visual aids. The target audience is homeowners and single-family home builders who have not yet understood the technical requirements of building codes and disaster-resistant construction. Each chapter presents a disaster-resistant construction topic, the construction typologies offered and the reasoning for the options offered. Without trained engineers, architects, or contractors familiar with the NSCP provisions, a homeowner or builder who follows the guidelines' recommendations would be able to build a more disaster-resilient house.

5.2 Chapter Contents

Chapter One introduces two major hazards in the Philippines – earthquakes and typhoons. It also provides preparedness guides for these natural disasters.


Handbook for Disaster-Resistant Houses

Where the world's tropical cyclones form

Each year on the average 100 tropical storms form in the world. About two-thirds of them grow into 74 mph or stronger hurricanes, typhoons or cyclones.

USA Today, The Weather Book (1992)

WHAT IS A TROPICAL CYCLONE?

A Tropical Cyclone (known as "Bagyo" in the Philippines) is the generic term for an intense circulating weather system over tropical seas and oceans. It is accompanied with very strong winds, heavy rains and large ocean waves.

On the average, 100 tropical cyclones form in the world annually; two-thirds become typhoons and hurricanes.

WHAT CAUSES TYPHOONS?

Typhoons are caused by local atmospheric disturbances in the tropics, where ocean surface temperatures and humidity are high.

WHERE DO TYPHOONS OCCUR?

Typhoons occur mainly in the western Pacific Ocean. Typhoons often cause huge damage to coasts and islands that are on their path. They usually start close to the equator and move westward, gathering size and intensity as they move.

Tracks and Intensity of Tropical Cyclones, 1851-2006

National Aeronautics and Space Administration (NASA)

1-5

BUILD CHANGE

Fig. 2. Chapter One – Earthquake and Typhoon Hazards in the Philippines (Build Change, 2015)

Chapter Two helps a homeowner choose the appropriate construction typology for her or his house. It provides a thorough explanation of every feature of the house that affects its performance in a disaster. The chapter emphasizes the need for simple house configurations, strong connections, and good material and construction quality.

Chapter Three provides advice to homeowners and builders on how to choose good quality materials. It demonstrates how to do on-the-spot tests to gauge the quality of construction materials, provides guidance for correctly proportioning concrete, grout and mortar mixtures, instruction on how to achieve optimum strength of concrete through proper curing methods, and suggestions for how to protect construction materials in storage before start of construction.

Chapter Four discusses concerns about choosing the correct site. This is especially useful for homeowners who have not yet chosen their site or may have the opportunity to relocate from their current plot. Chapters Five to Seven cover the important elements of reinforced concrete and masonry systems, such as building strong foundations, masonry walls, and concrete columns and beams. Proper methods for mixing, pouring, vibrating, and curing concrete and grout are discussed in more detail in these sections.

Timber-framed wall construction is covered in Chapter Eight. In the Philippines, timber walls are generally viewed as coverings and partitions and not expected to by typhoon-resistant---thus many homeowners would prefer to build a more expensive masonry house, which they view as being sturdier. This chapter presents four options for timber-framed lateral-force resisting systems adequate for winds speeds prescribed by the NSCP. Three of these options are shear wall systems, which can be used with the 250 kph basic wind speed in Wind Zone I. The fourth, a post and beam system, can only be used Wind Zone III, as specified in the NSCP, where basic wind speed is 150 kph. The regions where these systems are applicable is clearly stated in the Guidelines.

Chapter Nine covers Roof Construction. Two timber roof options are presented: a Rafter and Tie System, for roofs with widths of 3.5 meters or less; and Truss Roofing System, for larger roofs. Best practices for installing roof sheeting are discussed in this chapter along with how those practices provide wind- and water-resistance.

Chapter Ten succinctly summarizes the minimum requirements of the elements that are discussed in the preceding chapters in a bulleted list form. This is convenient while building for quickly checking the numerical values of the minimum standards that should be followed. Similarly, it is also helpful for a homeowner to flip through these pages to check if the construction of her or his residence complies with the minimum design standards that are stated in the Residential Design and Construction Guidelines.

6. Conclusions

The Guidelines provide illustrated and simplified instructions for disaster-resistant design and construction, addressing the absence of a standard of residential construction that the majority of homeowners in the Philippines can utilize. As climate change continues to threaten disaster-vulnerable communities like the Philippines, building local capacity is critical to promote housing resilience. Current researchers suggest that technical advancements, such as BIM technologies, are essential in ensuring accuracy and thus providing safer housing construction, however, there are still barriers in utilizing capability of technologies specially in organizational level (Rajabi et al., 2022; Rajabi et al., 2022). Providing evidence-based interventions and technical knowledge may aid in advancing resilience. Increasing understanding and application of the Guidelines in residential construction in earthquake- and typhoon-prone areas will increase the structural safety of houses and the country's resiliency. Further recommendations to ensure that technical knowledge will promote resilience are building local capacities, such as providing technical assistance to local builders and homeowners. Additionally, current studies suggest that coordination among stakeholders, specifically government agencies, organizations, and community leaders, is essential in providing lasting solutions to build housing resilience (Opdyke et al., 2017; Ourang, 2022).

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