# EVALUATION OF PERFORMANCE OF TAIWAN HOUSING STOCK AND SCHOOLS DURING THE $M_W$6.4 KAOHSIUNG/MEINONG EARTHQUAKE OF FEBRUARY 6, 2016

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## Abstract

The recent Kaohsiung Meinong Earthquake which occurred on February 6, 2016 affected several categories of building stock for which risk identification programs were previously developed by NCREE.

A typical building type in the city of Tainan is a mixed-use three-to-five-story structure. The ground floor of this typical structure is an open-front commercial or manufacturing space, which is laterally a soft story. The upper floors are residential and extend over a covered sidewalk, with column supports at the front of the building. NCREE has an established “street house” program which provides criteria for homeowners to evaluate and retrofit these structures. This program is discussed below, as well as damage and structural deficiencies related to this type of structure that were observed during a field reconnaissance trip following the Meinong Earthquake.

An active evaluation and retrofit program is in place for school buildings in Taiwan. This program identifies buildings with seismic deficiencies and determines whether or not a retrofit is warranted. The program and retrofit strategies are discussed, as well as the performance of schools with and without retrofit during the Meinong Earthquake.

## Introduction

The performance of a region’s building stock in a major earthquake is affected by several parameters, including the age of the buildings, the design codes in effect at the time of their construction, and the degree to which the construction conforms with the design codes. Different countries have set varying criteria for acceptable losses, often tied to the cost to achieve desired performance levels. Resiliency, or the ability of a community to recover following a natural disaster, can be tied to the extent of losses a community suffers: the higher the losses, the more difficult the recovery that the region can expect.

Design codes directly determine losses by setting acceptable thresholds to prevent building collapse. For modern codes many countries specify the maximum considered earthquake (MCE) based on an approximately 2500-year return period (Figure 1). This results in a probability of exceeding the MCE of 2% in a 50 year time period. Considering a 1.5 lower bound margin on the inherent strength and collapse resistance of a structure, this results in a 10% probability of collapse at the MCE ground motion. (ASCE 7-10/ATC 63)

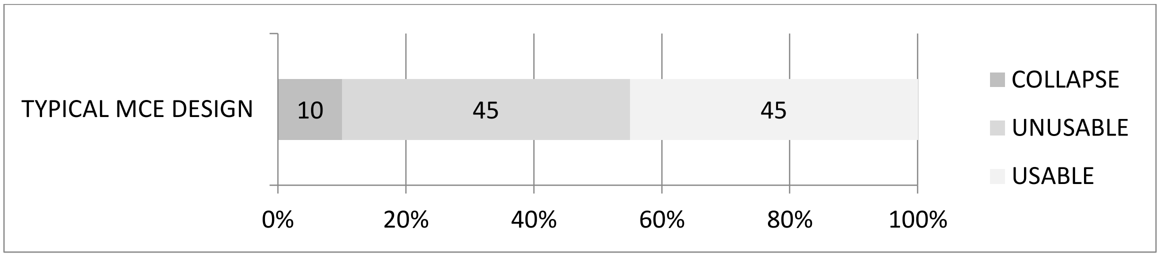


***Figure 1:*** *Design code's assigned probability of collapse, major damage rendering a building unusable, and minor damage permitting building usage (ASCE 7-10, ATC 63).*

While the engineering design community has calculated and accepted this level of risk, it is a concept about which the public is not knowledgeable. Coupled with the fact that many buildings were designed before seismic loads were included in a country's or city's building codes, the expected performance can be much worse. Consider recent earthquakes for which the number of buildings classified as either collapsed or severely damaged were reported (Figure 2). The maximum considered earthquake may be exceeded for some building periods but not for others. In some countries like Chile, where the use of high shear wall density is common, the building stock performs much better even for an MCE. In other countries, where the building stock includes many older structures, the performance is much worse than the current risk levels accepted in building codes.

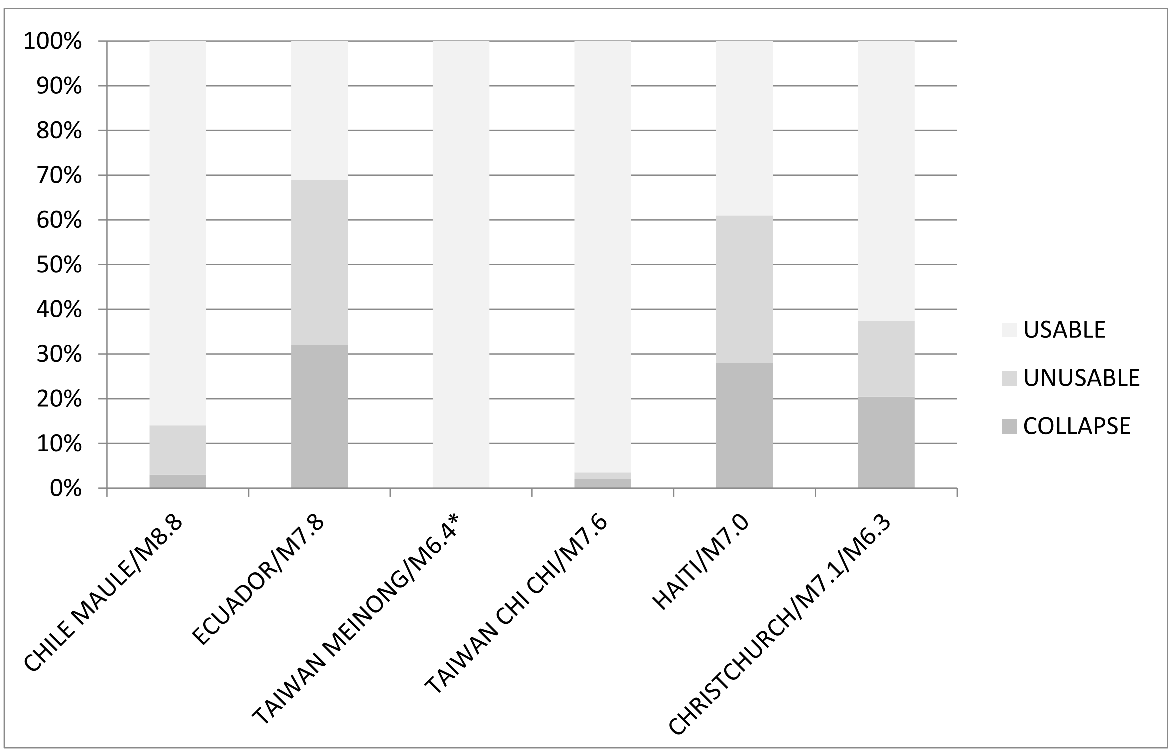


***Figure 2:*** *Percentage of collapse, major damage rendering a building unusable, and minor damage observed in recent earthquakes. * Less than 1%. (EERI, NCREE,USGS,USAID)*

Even in countries where the percentage of buildings in a major earthquake performs better than the expectations of the design codes, the losses can still be substantial when reviewed in terms of lost housing units, deaths, and economic impacts (Figure 3).

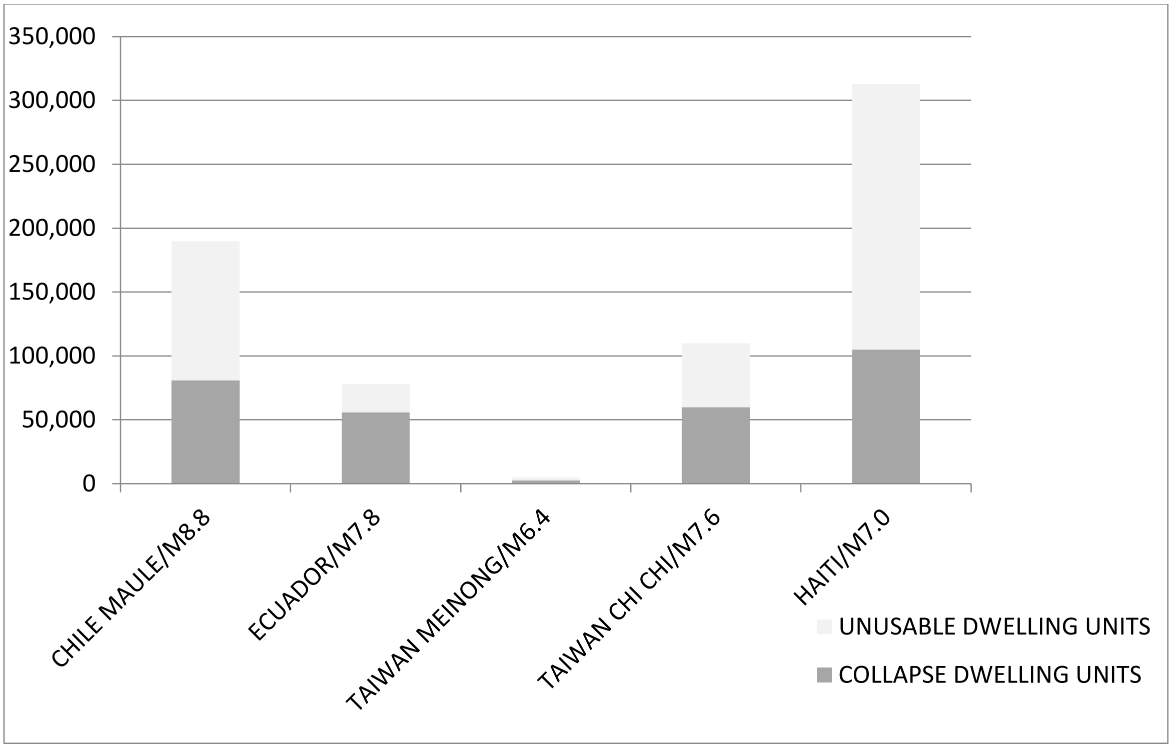


***Figure 3:*** *Percentage of collapsed housing units and unusable housing units. (EERI, NCREE, USGS)*

**Taiwanese Construction.** There are 5 major types of buildings in Taiwan: concrete framed buildings, high rise steel office buildings, street houses and individual single-family homes, and school buildings (Figure 4).

The majority of housing in Taiwan consists of "street houses" particularly in urban areas. The development of the street house started during the Qing dynasty around 1683. A typical street house is a row of attached buildings under 5 stories, with a 12 -15 ft wide pedestrian arcade. The first floor is typically utilized for commercial purposes. The second and higher floors are residential. Street houses were made of wood or brick until the 1970's when reinforced concrete frames became more common. Due to natural disasters and poor maintenance, the wood or brick street houses have nearly disappeared.

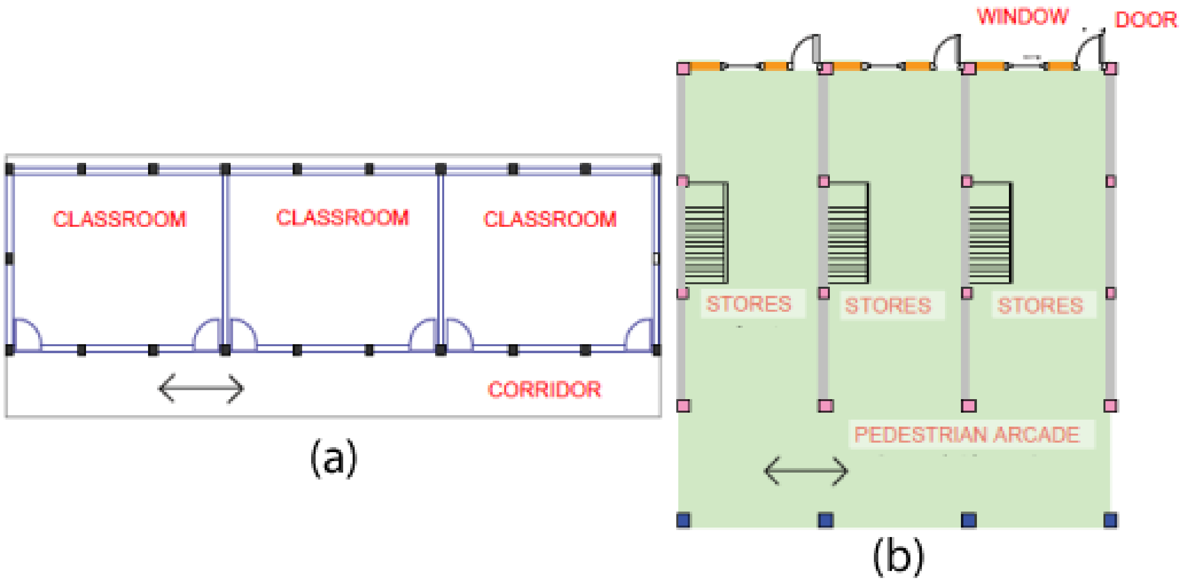

***Figure 4:*** *Typical Floor Plans (a) School Building; (b) Street House*

During an earthquake, these buildings typically fail at the first floor, parallel to the "long" direction (i.e. "street direction") of the building. The amount of wall area parallel to the street is significantly less at the first floor than at the floors above, and also less than that in the "short" direction.
For a typical school building, windows are needed for natural light. The classrooms are connected to a corridor on one side. Similarly, the street houses are built with less wall area at the first floor to accommodate a commercial store in the front. The pedestrian arcade below the second floor along the buildings enables people to walk between stores without getting wet from the sub-tropical rains. In addition, 90 percent of both building types are between two and four stories high. The column sizes are usually the same throughout the height of the building with their smaller plan-width parallel to the street.

**School Evaluation and Retrofit Program.** Following the 1999 Mw7.6 Chi-Chi Earthquake, an evaluation and retrofit program for school buildings was started. NCREE recognized during the reconnaissance of that earthquake that severe damage was observed predominantly in school buildings and street houses. School buildings were chosen as an area of focus due to the sensitivity of the occupants as well as the use of school buildings as emergency shelter. Since the start of the program, analytical methods have evolved; additional data have become available from school performance in more recent earthquakes and in-situ tests have been performed to validate the results of analytical procedures. The current evaluation and retrofit procedure follows (1) a screening evaluation, (2) detailed evaluation, and (3) retrofit design.

The screening evaluation consists of a simple "capacity to demand" comparison based on the ratio of ground floor column and wall areas to building total floor area. The relationship is shown in equation (1). This equation is a simple screening metric based on detailed analyses conducted on 3,504 buildings, 2,922 of which are typical school buildings (Chiou *et al.*,2014).

$$I_s = \frac{Capacity}{Demand} = \frac{\sum \tau_c \mathrm{A_c} + \sum \tau_w \mathrm{A_w}}{a_g \times W \times \sum A_f} \qquad (1)$$

where $\tau_w$ and $\tau_c$ are column and wall strength adjustment factors, $A_c$ and $A_w$ are the ground floor column and wall areas, $a_g$ is the design ground acceleration, $W$ is the seismic weight and $A_f$ is the total building floor area.

If the screening evaluation result in a Capacity/Demand ratio ($I_s$) that exceeds 0.8, the school building is subjected to a more detailed analysis: The detailed analysis procedure - referred to as Taiwan Earthquake Assessment for Structures by Pushover Analysis (TEASPA - is a non-linear static pushover analysis similar to those used in ATC-40 and ASCE-41. TEASPA calculates the ultimate seismic base shear capacity of the structure and then uses the results to compute the building capacity in terms of peak ground acceleration (*Ap*) for comparison to the code derived peak ground acceleration. The TEASPA method is tuned to the specific building stock of low rise, lightly reinforced (< 2% $A_c$) concrete moment frames (i.e. typical school building) to achieve realistic results. Plastic hinge properties are based on experimental results specific to this building type. The analysis results of the TEASPA methods have been verified by numerical modeling and validated thorough in-situ full scale testing of representative building stock by Hsiao and Fu-Pei (2014).

The analyzed school buildings with insufficient strength are tagged for retrofit. A solution is developed to strengthen the building to meet the required demand under the peak ground acceleration (Figure 5) . Typical reinforcing schemes include the introduction of new moment frames, shear walls, jacketing of columns or introducing shear panels adjacent to existing columns.

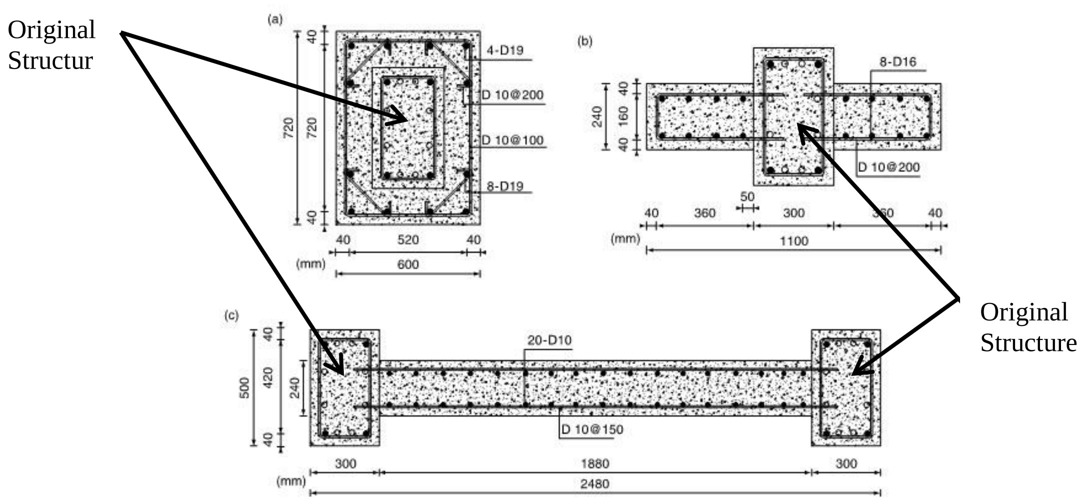


***Figure 5:*** *Typical Reinforcing Cross Sections: (a) Existing Column Jacketing; (b) Shear Panels Adjacent to Existing Columns; Shear Wall Between Existing Columns (Hsiao et al. 2014)*

The performance of school buildings in Taiwan after the Meinong earthquake, further verified the assessment method and retrofit schemes of the school retrofit program supported by NCREE is successful and accurate (Figures 6 and 7). In the Tainan area (near the event epicenter), none of the 58 retrofitted schools were observed to have structural damage. Eighteen of the 85 (21%) school buildings earmarked for retrofitting were observed to have severe damage. Of the school buildings that passed the screening evaluation, only 1 of the 158 (0.6%) buildings was found to suffer severe damage (Figure 8).



***Figure 6:*** *Guiren Middle School Retrofitted with Added Moment Frame (Minor Damage)*

***Figure 7:*** *Guiren Middle School Retrofitted with Jacketed Column (No Damage)*


***Figure 8:*** *Yujing Junior High School Not Retrofitted (Severely Damage)*

**Street House Evaluation Program**. Based on the database of detailed seismic evaluations of 1,187 school buildings, NCREE has developed a preliminary assessment program for the "street house" buildings by using regression analysis. This method was validated by NCREE internally with an evaluation of 59 street houses damaged in previous earthquakes, including the Mw7.6 Chi-Chi earthquake (1999), Mw6.6 Jiaxian earthquake of March 4, 2010, Mw6.0 Nantou earthquake of March 4, 2013. NCREE beta tested the program using 145 sample street houses throughout the island of Taiwan. Applying the same preliminary assessment method used for school buildings, the results showed that 40 percent of the street houses reviewed required a detailed assessment. This comparison provides a rough estimate of the amount of the housing requiring assessment throughout Taiwan.

A simplified version of the preliminary assessment method is provided to the public on the NCREE website (http://school.ncree.org.tw/school/index.html). With input of simple information (building stories, approximate year built, building depth and width, column sizes, column quantities, and wall length, etc.), the web program carries out a preliminary analysis to determine if the building has a sufficient seismic load capacity. If the preliminary results suggest the building does not have adequate capacity, then a detailed assessment is required. The NCREE street house website (http://streethouse.ncree.narl.org.tw/) also introduces a few preliminary reinforcing ideas similar to those recommended for school buildings.

**Analysis**. From the school detailed evaluation data base, typical building material parameters are available. This data were used as supplemental information along with measured field dimensions in order to analyze two case study “street house” buildings with observed failures during the Meinong earthquake. Preliminary analysis was carried out in accordance with the NCREE “street house” evaluation program. This work is being followed up with 3D finite element models of the two case study structures utilizing data recorded at seismograph stations in proximity to the two sites. All are summarized in Table 1.

**Case Study I.** Multi-family street house in Yujing District with six bays parallel to the street (Figure 9).

**Case Study II.** Multi-family street house in Tainan’s Guiren District with twelve bays parallel to the street and five transferred columns at the first floor level (Figure 10).



***Figure 9:*** *Case Study I, Yujing district “street house”*

***Figure 10:*** *Case Study II, Guiren Tainan “street house”*

**Table 1.** Typical Properties and Case Study Parameters

| (1) Column sizes, (2) Column reinforcement ratio, (3) Concrete compression strength ($f^1_c$), (4) Column tie spacing, (5) Wall thickness, (6) Concrete wall shear strength, (7) Solid brick wall shear strength | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Computed |
| Typical Parameters School House | 8”x16” 20cm x 40cm | 1.7-2% | 2500 psi 175kgf/cm$^2$ | 10”-12” 25-30cm | 8” 20cm | 4 sides restrained: 300psi (21kgf/cm$^2$) 3 sides restrained: 170psi (12kgf/cm$^2$) | 4 sides restrained: 55psi (3.9kgf/cm$^2$) 3 sides restrained: 38psi (2.7kgf/cm$^2$) | |
| Typical Parameters Street House | 8”x16” 20cm x 40cm | 1.94-2.16% | 2150psi 150kgf/cm$^2$ | 10”-12” 25-30cm | 8” 20cm | 4 sides restrained: 300psi (21kgf/cm$^2$) 3 sides restrained: 170psi (12kgf/cm$^2$) | 4 sides restrained: 55psi (3.9kgf/cm$^2$) 3 sides restrained: 38psi (2.7kgf/cm$^2$) | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Case Study 1<br>(Interior shear wall failure observed) | 35cm x 35cm and<br>20cm x 35 cm | ASSUME TYPICAL | ASSUME TYPICAL | 20 cm | 20 cm | ASSUME TYPICAL | ASSUME TYPICAL | CFR=.00577<br>Ap= 0.242<br>At=0.28<br>E= 0.867<br>Is=0.82<1 |
| Case Study 2<br>(Exterior column failure observed) | 19" x 20"<br>48cm x 51cm<br>12"x12" stirrups<br>30x30cm | 2.2% | ASSUME TYPICAL | #3@9"o.c.<br>(23cm) | 10"<br>(25cm) | ASSUME TYPICAL | ASSUME TYPICAL | CFP=0.0016<br>Ap=0<br>E=0<br>Is=0 |

CONCLUSIONS: Assessments of building performances following the Meinong Earthquake show that resiliency was dramatically improved as a result of the building assessment and retrofit programs implemented by the NCREE. This is verified by the observations in Tainan where (a) none of the 58 retrofitted schools were observed to have structural damage, (b) only 18 of the 85 (21%) school buildings earmarked for retrofitting were observed to have severe damage, and, (c) of the school buildings that passed the screening evaluation, only 1 of the 158 (0.6%) buildings was found to suffer severe damage.

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