Wood-frame construction in past earthquakes

Rainer, J. Hans[1], Karacabeyli, Erol[2]

ABSTRACT

A survey was carried out of damages caused by eight earthquakes in locations where wood-frame construction was well represented and where some quantitative ground motion information was available. The main trends of structural behaviour and damage in each of these earthquakes are noted, together with the peak ground acceleration that these structures likely experienced. The main shortcomings that became evident in wood-frame construction are summarized. The survey showed that most one-storey residential buildings of wood-frame platform construction survived earthquake ground shaking with peak accelerations of over 0.6 g without loss of life, and many with little damage. Multi-storey buildings suffered more damage and a few collapsed, resulting in casualties. On the basis of typical strong-motion response spectra it is shown that the multi-storey structures received the most intense shaking and this, in addition to a weak first storey, explains the serious damage that some of these buildings have sustained. Recommendations are made for seismic requirements of multi-storey conventional wood-frame construction and for installation of more strong-motion instruments in wood-frame buildings.

INTRODUCTION

Wood-frame construction is by far the most common housing type in Canada, the USA and New Zealand for single-family and low-rise multi-family dwellings. This type of building is also gaining acceptance in other parts of the world, including Japan. In the last few decades a large number of wood-frame buildings have been subjected to earthquakes; this provides an opportunity to assess the general seismic performance of this type of construction and to relate the performance to quantitative indicators of ground shaking such as peak ground acceleration and response spectra.

Elements of Wood-frame Construction

The typical modern wood-frame house consists of a concrete foundation (also sometimes concrete block masonry), whereupon a platform is constructed of joists covered with plywood or oriented strand board (OSB) to form the floor of the ground level of the house. This platform is connected to the foundation either directly with anchor bolts, or via a short so-called “cripple wall” or “stub wall”. On this base the exterior and interior walls are erected. The walls consist of a horizontal sill plate and nominally 2 inch by 4 inch (38 mm by 89 mm) or 2 inch by 6 inch (38 mm by 140 mm) verticals of one storey height at a spacing of typically 40 cm. Onto these verticals are nailed plywood or OSB on the outside of the building, the inside spaces are filled with thermal insulation and then covered with a vapour barrier and gypsum board interior finish. The roof structure, consisting of prefabricated trusses, is attached to the top plate of the walls. The interior and exterior is then completed to various consumer preferences. Further details can be found in Kesik (1997). Multi-storey wood-frame construction follows the same basic pattern as each succeeding floor is added on top of the previous one.

PARAMETERS THAT GOVERN SEISMIC RESPONSE OF BUILDINGS

Theoretical considerations and observations of a number of earthquakes as well as calculations and laboratory experiments have shown the following parameters to govern the seismic response of buildings:

- the characteristics of ground movement at the building site (amplitude, duration, frequency content);
- the dynamic characteristics of the building (natural modes, frequencies and damping);
- the deformational characteristics of the building (stiffness, strength and ductility);

[1] Visiting Scientist, Forintek Canada Corp., Vancouver B.C., V6T 1W5, Canada
[2] Group Leader, Wood Engineering Dept., Forintek Canada Corp., Vancouver B.C., V6T 1W5, Canada

- the building regulations that were followed in design and construction (year and type of code and standard, engineered design or construction by conventional rules).

All of these parameters have to be taken into account when seismic behaviour of buildings (or any other structure) is considered. For earthquake resistance and compared to other building types, wood-frame construction has some inherent advantages that derive from high strength-to-weight ratio, high degree of redundancy, and considerable damping and ductility.

BEHAVIOUR OF WOOD-FRAME CONSTRUCTION IN PAST EARTHQUAKES

General Approach

As can be appreciated from the previous discussion of factors that affect the seismic performance of buildings, the process is a complex one and difficult to analyze, especially for wood-frame construction since a large number of diverse components are involved in resisting the seismic actions. Fortunately, many of the earthquakes in the last 30 to 40 years have yielded a significant amount of instrumental data on how the ground had moved, along with surveys of damage or non-damage. From these data, contour lines can be drawn of equal intensity of shaking (or of many another parameter). Peak horizontal ground acceleration (PGA) is employed here in the interpretation of observed seismic behaviour. Because instrumented ground motion stations are still relatively sparsely distributed, however, drawing contours through a small data set must be recognized as being approximate since even over small distances some variation of ground motions can occur. On a statistical basis, however, this procedure can be expected to provide useful information concerning dominant trends.

Since this survey confines itself to wood-frame construction, only those earthquakes will be examined where these types of buildings were particularly affected and where, aside from Alaska, strong-motion seismic records were available. Included are: Alaska Earthquake, 1964; San Fernando Earthquake, California, 1971; Edgecumbe Earthquake, New Zealand, 1987; Saguenay Earthquake, Quebec, 1988; Loma Prieta Earthquake, California, 1989; Northridge Earthquake, California, 1994; and Hyogo-ken Nanbu Earthquake, Kobe, Japan, 1995.

Alaska Earthquake, 1964

The Alaska Earthquake of Magnitude 8.4 was one of the largest earthquakes in North America in this century and was characterized by intense ground shaking that caused major landslides in the populated area of Anchorage. Unfortunately, no recordings of ground motions were obtained. The performance of wood-frame houses was punctuated by the structural integrity of buildings that literally slid down failed slopes or were otherwise subjected to large ground movements. Although some houses collapsed, many of the box-like wood-frame structures stayed intact and “rode out” the earthquake, only to come to rest in an unusable orientation. For further details see US Dept. of Commerce (1967).

San Fernando Earthquake, California, 1971

This earthquake of Magnitude 6.7 occurred in a northerly suburban area of Los Angeles and consequently affected a large number of single-family homes as well as hospitals and commercial buildings and resulted in 64 deaths. From a contour map drawn from recorded peak ground accelerations (TriNET SHAKE MAPS 1999) it may be observed that the residential areas of San Fernando experienced peak horizontal ground accelerations (PGA) of 0.6 of gravity (g) and greater.

Older wooden houses in the San Fernando area suffered damage ranging from minor to partial collapse. Newer two-storey apartment buildings with large ground-level openings were also severely affected. See Figure 1. These damage cases can be categorized as follows: houses sliding off the foundations; collapse of cripple walls in crawl space; collapse of add-ons such as porches; collapse of masonry chimneys; major distortion of weak first storey. A detailed damage survey is presented by the Pacific Fire Rating Bureau (1971).

Aside from these specific types of failures, the majority of the then-modern wooden houses performed well, especially when the life-safety objective is considered. Even where the building slid off the foundation, the chimney failed or the cripple wall collapsed, the remainder of the building stayed intact and prevented serious injury or death to occupants.

Figure 1 Damaged two-story building with weak first storey; San Fernando Earthquake, 1971.

Edgecumbe Earthquake, New Zealand, 1987

This event on the North Island consisted of a main shock of Magnitude 6.3, preceded by 7 minutes by a Magnitude 5.2 fore-shock, and followed by four aftershocks with Magnitudes greater than 5. These quakes were centred in a rural area and small towns. The only ground motion record obtained came from the base of the Matahina Dam, over 20 km from the epicentre of the main shock, with a peak horizontal ground acceleration (PGA) of 0.32 g. The town of Edgecumbe (population 2000) may have experienced greater accelerations since it is located only about 8 km from the epicentre of the main shock. No deaths or serious injuries were reported by Pender and Robertson (1987). Of the nearly 7000 houses in the affected region, fewer than 50 suffered substantial damage but none collapsed. Damage consisted of houses sliding off the foundation, cracking and collapse of the brick veneer on the building exterior, collapse of chimneys and failure of foundation posts and roof struts.

Saguenay Earthquake, Quebec, 1988

Although the Saguenay Earthquake in northern Quebec, Canada, with Magnitude 5.7 was not as powerful as some of the others surveyed here, it was the largest earthquake in the last 50 years in eastern North America. Furthermore, a relatively large number of ground motion records were obtained. The epicentre was located in a lightly populated area 150 km north of Quebec City. Peak ground accelerations in the population centres of Chicoutimi, 36 km from the epicentre, and on the north shore of the St. Lawrence River, 100 km away, were of the order of 0.12 to 0.17 g. The ground motions consisted mainly of high frequencies. Most of the damage to wood-frame buildings up to 2 storeys was limited to cracks in chimneys, foundations and brick veneer walls (Poultre et al. 1993). No cases of near-collapse of houses or deaths were reported.

Loma Prieta Earthquake, California, 1989

The Loma Prieta Earthquake, with Magnitude 7.1, had its epicentre 100 km south of San Francisco, but its effects reached well beyond to Oakland on the north shore of San Francisco Bay. Total casualties were 62 deaths and over 3000 injured; 49 persons died in the collapse of the double-deck freeway in Oakland. A contour map constructed from the recorded peak ground accelerations was presented by Rainer et al. (1990).

A number of older four-storey wooden apartment buildings located on fill materials in the Marina Bay district of San Francisco collapsed onto the ground floor that consisted entirely of garage openings and therefore represented a very weak first storey. Further details can be found in Bruneau et al. (1990). Wood-frame houses located in and near the epicentral region survived the shaking mostly with repairable damage. Some of these houses near the epicentre were likely subjected to peak ground accelerations as large as 0.5 g and possibly larger.

Northridge Earthquake, California, 1994

The Northridge Earthquake with Magnitude 6.7 was notable for its high ground accelerations, both horizontally and vertically, which in places exceed the acceleration of gravity (1.0 g). A contour map of peak horizontal ground accelerations is presented by TriNET SHAKE MAPS (1999). The earthquake caused extensive damage to residential, institutional, and commercial buildings and to the highway and freeway system of this area about 20 km northwest of Los Angeles. This represented the most intense ground shaking that had so far been recorded in a populated area in North America. Over 60 persons were killed and estimates of property losses range from 30 to 40 billion US$.

This earthquake again drew attention to a weakness that had already been recognized (practically next door) in the 1971 San Fernando earthquake - the weak first storey in multi-storey wood-frame apartment buildings. In Northridge, a number of apartment complexes collapsed onto the first storey and killed 16 occupants. Such collapses are perhaps not surprising when one considers that the horizontal ground accelerations, combined with the vertical accelerations of comparable amplitude, exceeded the nominal horizontal design acceleration of 0.4 g by factors of 2 and more. Four deaths also occurred in three single-family houses that collapsed upon sliding down a hillside.

Despite these tragic failures, other wood frame construction performed exceedingly well (NAHB Research Center 1994). As in other earthquakes, chimneys were severely damaged, while the rest of the building survived without significant problems.

Hyogo-ken Nanbu Earthquake, Kobe, Japan, 1995

The earthquake that hit the city of Kobe in the Hanshin area of Japan on January 17, 1995 was so far the most damaging earthquake in modern times, with estimated losses of well over 100 billion US$ and over 6000 deaths. Among the widespread destruction there were also numerous recently constructed low- and high-rise buildings that survived the earthquake, some with no visible damage (CAEE 1995).

Peak ground acceleration as high as 0.8 g were recorded in densely populated areas; a large part of southern Kobe and the cities of Ashiya, Nishinomiya and Takarazuka experienced over 0.6 g peak ground acceleration. The wooden houses hardest hit were those constructed before and immediately after World War II (BRI 1996). These structures consist of post-and-beam wood framing, with walls formed by horizontal boards nailed to the uprights, in-filled with bamboo webbing and covered with clay. Heavy roofs and the lack of lateral resistance made these structures particularly vulnerable to such a large earthquake and within the 0.6 g contour of PGA a majority of this type of building collapsed or was heavily damaged. This gave rise to devastating fires from broken gas lines and stoves; the interruption of the water supply greatly aggravated the situation.

Among the sea of devastation of older style houses were examples of modern wood construction and wood-frame houses (Figure 2) that showed no visible signs of distress (APA 1995). Of approximately 8000 “2 by 4” houses, none collapsed and 70% reported no damage (Two by Four news 1995). Most of these houses were located in areas of severe shaking and again demonstrate that modern wood-frame construction can withstand earthquakes with peak ground accelerations of 0.6 g or more with little or no damage.

Figure 2 Undamaged "2x4" wood-frame houses in Ashiya City near Kobe, Japan, after Hyogo-ken Nanbu Earthquake, 1995.

ASSESSMENT OF PERFORMANCE

A summary of the total number of casualties caused by the above earthquakes and number of deaths in wood-frame houses is presented in Table 1. Evidently, the number of deaths in wood-frame buildings is very low, considering the large number of buildings severely shaken.

Table 1. Overview of casualties in some recent earthquakes

Earthquake	M	No. of Persons Killed (Approx.)		No. of Wood-frame Bldgs. Shaken (Estimated)
		Total	In Wood-frame Buildings	
Alaska, 1964	8.4	130	<10	
San Fernando, 1971	6.7	63	4	100 000
Edgecumbe, 1987	6.3	0	0	7 000
Saguenay, 1988	5.7	0	0	10 000
Loma Prieta, 1989	7.1	66	0	50 000
Northridge, 1994	6.7	60	16 + 4	200 000
Hyogo-ken Nambu (Kobe), 1995	6.8	6 300	0	8 000

On the basis of observations of the performance of wood-frame buildings in the earthquakes surveyed the following assessment is made:

1. Single-storey wood-frame houses have performed well when subjected to PGA of 0.6 g and even higher, provided some well-known deficiencies such as unbraced stub-walls and inadequately braced additions such as porches and chimneys are absent. The performance has demonstrated that the life-safety objective inherent in building codes has been met. In fact, for most of the houses the damage sustained is of a minor nature, showing that the objective of damage control has also largely been achieved.
2. Some two-storey wood-frame buildings were seriously damaged in California in areas of 0.6 to 0.8 g PGA. In Kobe, on the other hand, they all performed well. In California they largely met the life-safety criterion, whereas in Kobe they met the life-safety criterion with minimal damage.
3. For three- to four-storey wood-frame buildings the life safety objective has largely been achieved for PGA of 0.6 g and larger during the Northridge earthquake, with the exception of a few buildings where weak first storeys led to collapse and casualties.

This pattern of behaviour will now be related to the loading demand of the earthquakes.

IMPLICATIONS FOR DESIGN

The loading imposed on the building by the seismic ground motion is depicted by the response spectrum, an example of which is shown in Figure 3. An examination of the acceleration response spectra for the Kobe, Northridge, Loma Prieta, Edgecumbe, and San Fernando earthquakes shows that the spectral response increases from the PGA at zero period to a maximum at a period of about 0.3 to 0.4 s. Given that the first natural period of single-storey houses are at an average of 0.13 s (Madearis 1978, Rainer et al. 1988), two-storey houses at 0.23 s, and three-storey houses (by extrapolation) at 0.33 s, it may be seen from Figure 3, for example, that the two or three-storey building is subjected to a larger spectral acceleration and consequently acquires the larger base shear than the single-storey building. If, in addition, the approximately 3 times greater additional mass for the three-storey building is taken into account, it may be seen that the base shear to be resisted by the three-storey building has to be many times larger than for the single-storey house. It then follows that if the same good performance is desired for the multi-storey wood-frame buildings as was demonstrated for the single-storey ones, the former will have to possess a base shear resistance per unit area many times that of a single-storey house. Conversely, construction of multi-storey wood-frame buildings to the same requirements as single-storey houses will not result in comparable seismic performance. This phenomenon is particularly important for the seismic-resistant construction of conventional multi-storey wood-frame buildings.

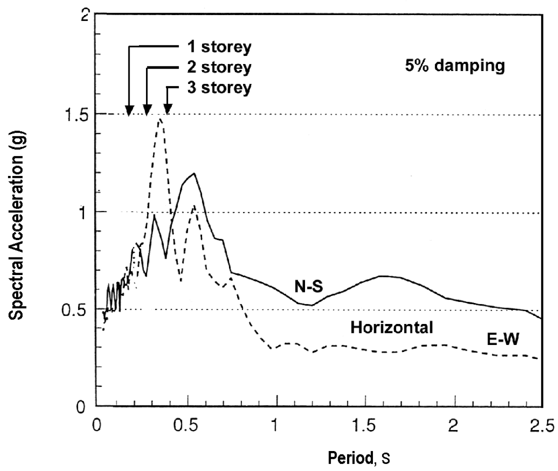

Figure 3 Response spectrum for Northridge Earthquake 1994, 18350 Rosco Blvd., Northridge, California. Adapted from Johnson and Pierepiekarz (1994).

RESEARCH FOR IMPROVED SEISMIC PERFORMANCE

Given the wide-spread use and economic importance of wood-frame construction in North America, New Zealand and other seismically active areas of the world, there is an ongoing need to ensure the life safety of inhabitants and to reduce the economic loss from earthquakes. In order to achieve this objective successfully, the seismic behaviour of these structures needs to be better understood and quantified. Thus a number of multi-faceted research programs into seismic behaviour of wood-frame construction have been launched, among others, by the Building Research Institute (BRI) of Japan, BRANZ in New Zealand, Forintek Canada Corporation in Canada, and the Wood-frame Project of the California Universities for Research in Earthquake Engineering (CUREe). In addition, many other institutions carry out research into one or more aspects of seismic behaviour of wood-frame construction, behaviour of joints and wall elements, mathematical modeling, component and full-scale testing, and development of design aids and codes and standards.

Strong-motion records of the performance of wood-frame houses are scarce or non-existent, nor are any plans for a comprehensive seismic instrumentation program of these types of structures known to the authors. Such records would add significantly to the understanding and quantification of behaviour of these widely distributed structures. While testing of individual components and full-scale shake-table experiments have provided and will continue to provide much useful information, the definitive test is still the performance of a real structure in a real earthquake!

SUMMARY AND CONCLUSIONS

An examination of the seismic behaviour of wood-frame construction in a number of recent earthquakes has shown the following:

- Single-storey wood-frame houses have performed well when subjected to PGA of 0.6 g and even higher, provided some well-known deficiencies such as un-braced stub-walls, and inadequately braced additions such as porches and chimneys are absent. The performance of these houses has demonstrated that the life-safety objective inherent in building codes has been satisfied. In fact, for most of the houses the damage sustained from earthquakes is of a minor nature, showing that the objective of damage control has also largely been achieved.
- Some two-storey wood-frame buildings were seriously damaged in areas of 0.6 to 0.8 g PGA in California. In Kobe, on the other hand, they all performed well. In California they largely met the life-safety criterion, whereas in Kobe they met the life-safety criterion with minimal damage.
- For three- to four-storey wood-frame structures the life safety objective has largely been achieved for PGA of 0.6 g and larger during the Northridge earthquake except for a few that collapsed and resulted in casualties. These failures were due to a weak first storey and earthquake motions that substantially exceeded the design criteria.

The observed behaviour of this type of construction was related to the characteristics of the ground motions and it is concluded that multi-storey wood-frame buildings need to be constructed to greater loading requirements than single-storey houses. This is particularly relevant to multi-storey buildings which are constructed according to conventional rules.

A comprehensive seismic instrumentation program for wood-frame structures should be implemented so that the performance can be observed quantitatively and further measures developed towards improved life safety and reduction in economic losses.

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