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Earthquake Risks and Effects of Earthquake Load on Behavior of Wood Frame Structure by Using International Residential Code (IRC)

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Abstract_ ***This paper discusses the earthquake-resistance implications of additions and alterations and provides recommendations and references for earthquake upgrades. This paper provides information on current best practices for earthquake-resistant house design and construction for use by builders, designers, code enforcement personnel, and potential homeowners at hill regions. It also introduces and explains the effects of earthquake loads on one- and two-family detached houses with wood frame structure and identifies the requirements of the 2003 International Residential Code (IRC) intended to resist these loads. The paper was a timely intervention aiming to strengthen the institutional capacities at all levels for reducing seismic risks, and to plan and implement earthquake risk reduction and disaster recovery preparedness measures in selected municipalities. The paper was greatly contributed to earthquake preparedness planning and safe construction practices for new buildings and retrofitting of existing poorly constructed unsafe buildings in Hilly regions. Post earthquake damage survey revealed that 90% of casualties result directly from the collapse of buildings that had usually no earthquake-resistant features. Mainly the paper enhanced the skills of construction engineers, architects and masons about safe building design and construction.***

Key words_ ***earthquake, construction, hill region, safe constructions, International Residential Code(IRC), wood frame structure***

I. INTRODUCTION

About 59% of India’s land area is under the threat of moderate to severe earthquake shaking intensity VII and higher. In the last 20 years, 8 major earthquakes have resulted in over 25,000 deaths. The regions far away from the Himalaya and other inter-plate boundaries, which were once considered to be relatively safe from strong shaking, have also experienced several devastating earthquakes. The huge losses of life and property in the earthquake-prone areas of the country have shown that the built-environment is extremely fragile, and country’s ability to respond to these events is extremely inadequate. Secondary events, such as landslides, fires, and tsunamis, account for the remaining 10% of the casualties. This emphasizes the need for strict compliance of town and country planning bye-laws and compulsory earthquake-resistant infrastructure design in India. In this paper various national initiatives taken up for the mitigation of earthquake and related hazards were discussed. Recent earthquake in India has demonstrated the need for seismic risk evaluation of building stock and consequences of future earthquakes. In India, where 90% of the population lives in buildings built without proper guidance from qualified engineers and architects, even a moderate intensity earthquake leads to substantial loss of life and properties. The rapid growth of cities, unplanned habitat, faulty structural design and poor quality construction techniques have also contributed to the proliferation of seismic risk. Evaluation of seismic safety of these constructions and adopting requisite retrofitting measures is a challenging task for the national government. Almost the entire northeast region, northern Bihar, Himachal Pradesh, Jammu & Kashmir and some parts of Gujarat are in seismic zone V (IS 1893 – 2002), while the entire Gangetic plain and some parts of Rajasthan are in seismic zone IV. In the last 20 years the country has experienced 8 major earthquakes that took more than 25000 lives and thereby affecting the local or regional economy. The effect would be substantial if such earthquakes hit metro cities where inappropriate developmental activities are alarmingly high. After Latur (1993, M6.3, 7928 deaths) earthquake, the state government undertook several post-earthquake risk reduction measures but the lesson has not been replicated to the neighboring state Gujarat till it was struck with devastating earthquake (M6.9) in 2001, which took more than 13800 lives. Post-earthquake damage survey in Indian context revealed that 90% of the causalities resulted directly from the collapse of buildings, out of which 60% are due to non-structural causes. In Gujarat state most of the buildings that followed Indian Standard guidelines and specifications have suffered little damages. Vulnerability analysis of 80 million housing stock lying in the seismic zone IV and V (Vulnerability Atlas of India, 2006) has not been carried out and so no preliminary estimate of damages is available for devising requisite strengthening measures. Till recently the Department of Agriculture and Cooperation had the nodal responsibility for managing natural disasters. After the Gujarat (2001) earthquakes this responsibility has been shifted to the Ministry of Home Affairs. 2 Potential earthquake threats in India The collision of Indian and Eurasian plates gave way to the formation of the great Himalaya. The Indian plate is still penetrating deeper at an estimated rate of about 50mm/year, causing intense seismic activity in the entire region. Five major earthquakes (M>7.5) (1897 Assam, 1905 Kangra, 1934 Bihar-Nepal, 1950 Assam and 2005 Kashmir) and 484 moderate to major quakes in the Himalayan Frontal Arc during the past 110 years have demonstrated the vulnerability of the entire surrounding region to

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earthquakes. Various scenario analysis have indicated that more than 100 million people are at seismic risks of varying magnitudes in the towns and villages of the hilly areas of the north and north east and the entire Indus-Ganga-Brahmaputra plain. The Koyna earthquake (1967, M6.3) in the stable continental region of India occurred after filling of Shivaji Sagar Lake, which raised the issue of seismic safety of mega hydel projects in India (Bilham et al., 2001).

Seismic Zoning

The seismic zoning maps indicate broadly the seismic coefficient that could generally be adopted for design of buildings in different parts of the country. The current map is an ad-hoc revision of 1970 zone map. These maps are based on subjective estimates of intensity from available information on earthquake occurrence, geology and tectonics of the country (Jain, 2007). A substantial effort is required for developing probabilistic zone map. The Indian seismic zoning is a continuous process which keeps undergoing changes as more and more data on occurrence of earthquakes becomes available. Currently efforts are being made towards seismic risk and hazard micro zonation of various urban establishments, such as Jabalpur, Sikkim, Guwahati, Delhi.

National Initiatives

The Yokohama Strategy (1994) emphasized that disaster response alone is not sufficient as it yields only temporary results at a very high cost. Disaster prevention, mitigation, preparedness and relief are four elements that contribute to the implementation of the sustainable development policies of any country. These elements along with environmental protection and sustainable development, are closely inter related. Therefore, in India for more than a decade each state is encouraged to incorporate mitigation strategies in their development plans and ensure efficient follow up measures at the community, sub-regional, regional, national and international levels. The Disaster Management Act, 2005 (DM Act, 2005) lays down institutional and coordination mechanisms for effective disaster management (DM) at the national, state, and district levels. As per this Act, the Government of India (GoI) created a multi-tiered institutional system consisting of the National Disaster Management Authority (NDMA), headed by the Prime Minister, the State Disaster Management Authorities (SDMAs) by the Chief Ministers and the District Disaster Management Authorities (DDMAs) by the District Collectors and cochaired by elected representatives of the local authorities of the respective districts. These bodies have been set up to facilitate the paradigm shift from the hitherto relief-centric approach to a more proactive, holistic and integrated approach of strengthening disaster preparedness, mitigation and emergency response.

Review Of Building Bye-Laws And Their Adoption

Structural mitigation measures are the key to make a significant impact towards earthquake safety. In view of this the States in earthquake prone zones have been directed to review, and if necessary, amend their building byelaws to incorporate the BIS seismic codes for construction in the concerned zones. An Expert Committee appointed by the Core Group on Earthquake Risk Mitigation has already submitted its report covering appropriate amendments to the existing Town & Country Planning Acts, Land Use Zoning Regulation, Development Control Regulations & Building Bylaws, which could be used by the State Governments & the local bodies there-under to upgrade the existing legal instruments. The Model Building Bylaws ensures the technical implementation of the safety aspects in all new constructions and upgrading the strength of existing structurally vulnerable constructions. To facilitate the review of existing building byelaws and adoption of the proposed amendments by the State Governments and UT administrations, no. of discussion workshops at regional level in the country have to be been organized. It is stressed that all planning authorities and local bodies are required to have development control regulations and building byelaws which would include multi-hazard safety provisions.

Revision Of Codes

An action plan has been drawn up for revision of existing codes, development of new codes and documents/commentaries, and making these codes and documents available all over the country including online access to these codes. An Apex committee consisting of representatives of Ministry of Consumer Affairs, BIS and MHA has been constituted to review the mechanism and process of development of codes relevant to earthquake risk mitigation and establish a protocol for revision by BIS.

Earthquake Engineering In Undergraduate Engineering/Architecture Curricula

The role of engineers and architects is crucial in reducing earthquake risks by ensuring that the constructions adhere to the norms of seismically safety. In view of this, the elements of earthquake engineering are being integrated into the undergraduate engineering and architecture courses. The model course curricula for adoption by various technical institutions and universities have been developed and circulated to the Universities and Technical Institutions for adoption in the undergraduate curricula. Ministry of Home Affairs is working with All India Council of Technical Education (AICTE) and Council of Architecture (COA) for introduction of revised curricula for engineering and architecture course from 2005-2006. The Ministry of Human Resource Development has initiated the National Program on earthquake Engineering Education in March 2003.

Urban Earthquake Vulnerability Reduction Programme

An accelerated urban earthquake vulnerability reduction programme has been taken up in 38 cities in seismic zones III, IV & V with population of half a million and above. 474 Orientation programmes have been organized for senior officers and representatives of the local planning and development bodies to sensitize them on earthquake preparedness and mitigation measures. The training programme for engineers and architects are being organized to impart knowledge about seismic safe construction and implementation of BIS norms. So far 1088 engineers and 825 architects have been trained. For enhanced school safety, education programmes have been organized in schools, colleges and other educational institutions. This programme will be further extended to 166 earthquake prone districts in seismic zones IV & V. Awareness generation programmes, community and neighborhood organizations have been started in these cities. These cities are also being assisted to review and amend their building bye-laws to incorporate multi hazard safety provisions.

National Guidelines On Earthquake Risk Management

National Disaster Management Authority has released a national guidelines in May 2007 in which it is mentioned that from June 2007 onwards all new constructions in the earthquake prone area must adopt earthquake resistant measures. The critical factors responsible for the high seismic risk in India has prioritised six sets of critical interventions; as the six pillars of earthquake management. They are to:

a) Ensure the incorporation of earthquake-resistant design features for the construction of new structures.

b) Facilitate selective strengthening and seismic retrofitting of existing priority and lifeline structures in earthquake-prone areas.

c) Improve the compliance regime through appropriate regulation and enforcement.

d) Improve the awareness and preparedness of all stakeholders.

e) Introduce appropriate capacity development interventions for effective earthquake management (including education training, R&D, and documentation).

f) Strengthen the emergency response capability in earthquake-prone areas.

II. MATERIALS AND METHODOLOGY

Earthquake-Resistance Requirements

This chapter explains the International Residential Code’s (IRC’s) general earthquake-resistance requirements as well as specific IRC requirements concerning load path and house configuration irregularities. One- and two-family detached houses of wood light-frame construction are addressed; however, the cold-formed discussion is relevant to other materials of construction likely to be used for detached houses including light-frame steel.

IRC General Earthquake Limitations

The variety of configurations used for houses is very wide and they are constructed of an equally wide variety of materials. IRC Section R301.2.2 imposes some limits on configuration and materials of construction for one- and two-family detached houses in Seismic Design Categories (SDCs) D1 and D2. These IRC limitations reflect the desire to provide equal earthquake performance for houses designed using the prescriptive IRC provisions and for those with an engineered design. Application of the prescriptive IRC requirements to houses that do not comply with the limitations can be expected to result in inadequate performance.

The limitations imposed by IRC Section R301.2.2 are as follows:

•Weight Limitations – For houses in SDCs D1 and D2, IRC Section R301.2.2.2.1 specifies maximum weights for the floor, roof-ceiling, and wall assemblies or systems. Because earthquake loads are proportional to the weight of the house, an upper bound on assembly weight provides an upper bound on earthquake loads. The specified maximum assembly weights relate directly to the weights considered in developing the IRC earthquake bracing provisions. The effect of the maximum weights is the exclusion of heavier finish materials when using the IRC provisions. Where heavier finish materials are to be used, an engineered design must be provided.

•House System Limitations – Another scope limitation for houses in SDCs D1 and D2 is given in the combined requirements of IRC Sections R301.2.2.3 and R301.2.2.4. These sections provide limits for number of stories based on building system and limits for anchored stone and masonry veneer and masonry and concrete wall construction.

•Story Height Limitation – IRC Section R301.3 provides a scope limitation that is not related solely to earthquake loads but rather applies in all SDCs. This section limits story height by limiting the wall clear height and the height of the floor assembly. This limits both the lateral earthquake and wind loads and the resulting overturning loads.

The IRC requires design in accordance with accepted engineering practice when the general earthquake limitations discussed above are not met (weight limitations, house configuration limitations, building system limitations, and story height limitations). Engineered design is addressed in Section R301.1.3. This section permits design to be limited to just the elements that do not conform to the IRC limitations. Increased assembly weight and story height will globally increase seismic and wind loads, generally making engineered design of the entire house necessary. Design of portions of the house is particularly applicable when an irregularity such as a cantilever, setback, or open front occurs. The extent of design is left to the judgment of the designer and building code official.

Load Path

For a house to remain stable, a load applied at any point on the structure must have a path allowing load transfer through each building part down to the building foundation and supporting soils. The term “load path” is used to describe this transfer of load through the building systems (floors, roof-ceilings, bracing walls).Basic Concept — To understand the concept of a load path, a house can be represented by the chain shown in Figure 2-1. The chain is pulled at the top and the load is transferred from one link to the next until it is transferred to the ground. If any link is weak or missing, the chain will not adequately transfer the load to the ground and failure will result.

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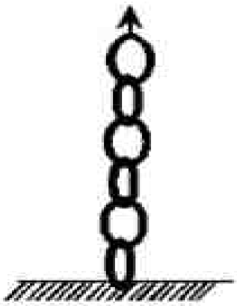


Fig. 1, chain illustrating the load path concept

Likewise, houses must have complete and adequate load paths to successfully transfer earthquake loads and other imposed loads to the supporting soils.

Load Path for Earthquake and Wind Loads — The example house in Figure 2 will be used to discuss load path. The arrows provide a simplified depiction of earthquake or wind loads pushing horizontally on the house. Although wind and earthquake loads can occur in any horizontal direction, design procedures generally apply the loads in each of the two principal building directions (i.e., longitudinal and transverse), one at a time, and this discussion of loading will utilize that convention.

Internally, the house has to convey loads from the upper portions of the structure to the foundation. For the example house, this is accomplished by transferring the loads through:
•The roof-ceiling system and its connections to the second-story bracing wall system,
•The second-story bracing wall system and its connections to the floor-ceiling system,
•The floor-ceiling system and its connections to the first-floor bracing wall system, and
•The first-story bracing wall system and its connections to the foundation, and
•The foundation to the supporting soil.

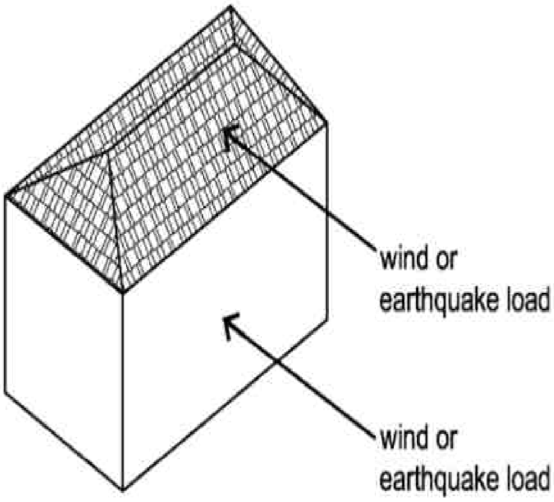
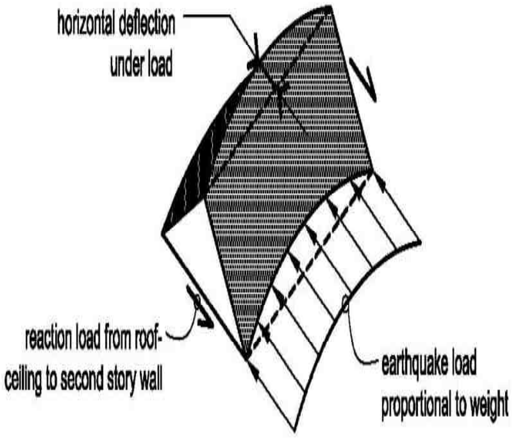
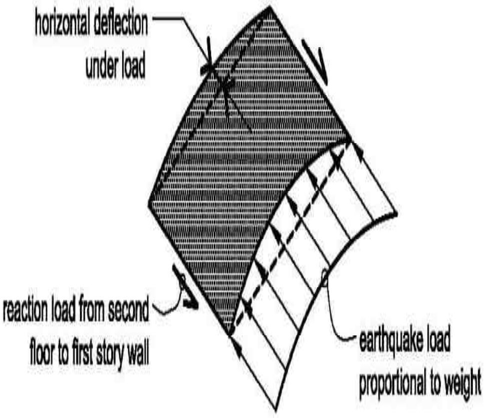


Fig. 2, Lateral loads induced in a building due to wind or earthquakes.

Roof-ceiling and Floor Systems — In the example house, the roof-ceiling system will resist horizontal earthquake loads proportional to the weight of the roof, ceiling, and top half of the second-story walls. The series of arrows at the right of Figure 2-3a depicts this load. The roof-ceiling system deflects horizontally under the load and transfers the load to the supporting walls at both ends. The single arrows at the roof-ceiling system ends depict the reaction loads to the supporting walls. Within the roof-ceiling system, the load is carried primarily by the roof sheathing and its fastening



(a) ROOF-CEILING SYSTEM



(b) 2ND FLOOR SYSTEM

Similarly, the floor system will resist horizontal earthquake loads proportional to its weight and the weight of walls above and below. As shown in Figure 2-4b, it will deflect and transfer load to the supporting walls in much the same way as the roof-ceiling system. Again, the loading is carried by the floor sheathing and its fastening .

Bracing Wall Systems – The roof-ceiling reaction load is transferred into the second-story bracing wall system as depicted by the arrow at the top of the wall in Figure 2-4a. The wall deflects under this load and transmits the load to the wall base and through the floor system to the first-story wall. Resistance to the wall load is provided by the wall sheathing and its fastening.

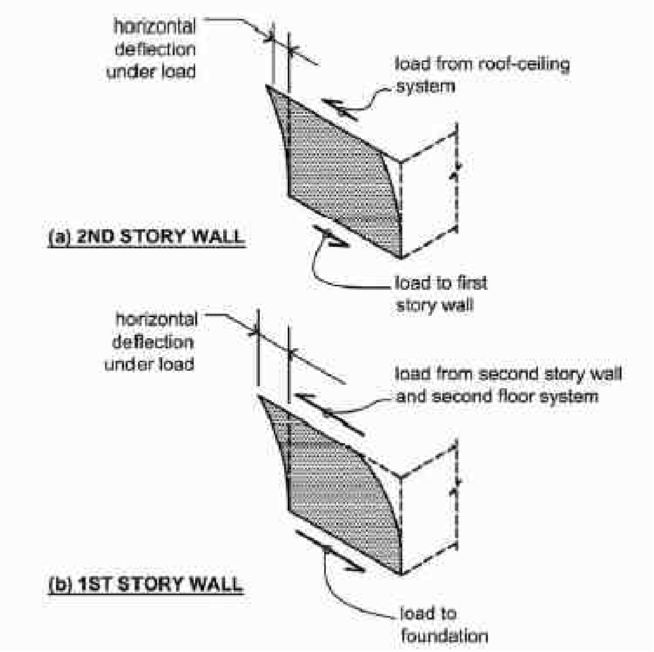


Fig. 2-4, Loading and deflection of bracing wall systems.

The first-story bracing wall system resists loads from both the second-story wall and the second-story floor system as depicted by the arrow at the top of the wall in Figure 2-4b. The wall deflects under this load and transmits the load to the wall base and the foundation. Again, resistance to the wall load is provided by sheathing and its fastening. Figure 2-5 provides an exploded view of the example house that illustrates the combination of roof-ceiling, floor, and wall systems and their connection to the foundation below.

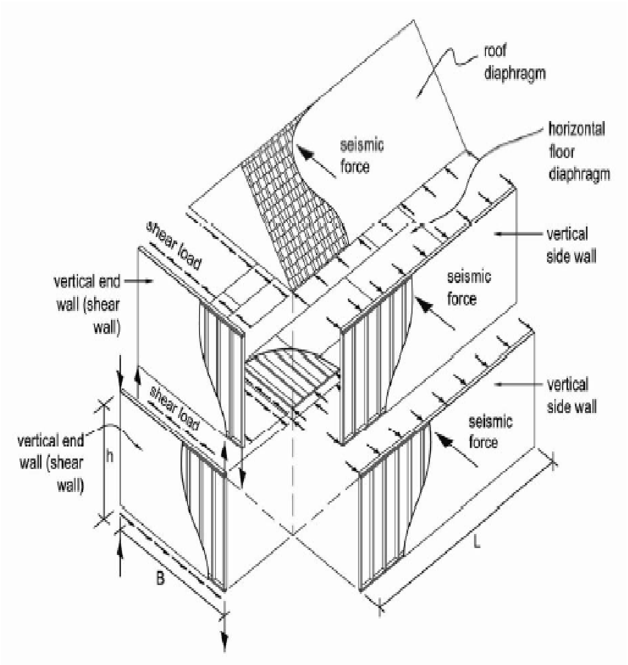


Fig. 2-5, Load transfer between components in a building.

Requirements for Connections Between Systems – As previously noted, a complete load path for earthquake loads requires not only adequate roof-ceiling, floor, and bracing wall systems but also adequate connection between these systems. Connections between systems must resist two primary types of loads: horizontal sliding loads and overturning loads.

Load Path Connection for Horizontal Sliding – Figure 2-6 depicts the end wall at the left side of the house illustrated in Figures 2-2 through 2-5 and provides a detailed illustration of one possible path for horizontal loads from the roof assembly to the foundation. The left-hand portion of the figure shows a section through the end wall in which each of the "links" in the load path is given a number, H1 through H11, corresponding to a connection or mechanism used to transfer the loads. The right-hand side of the figure shows an elevation of the same wall and illustrates the deformation that will occur if adequate connection is not made.

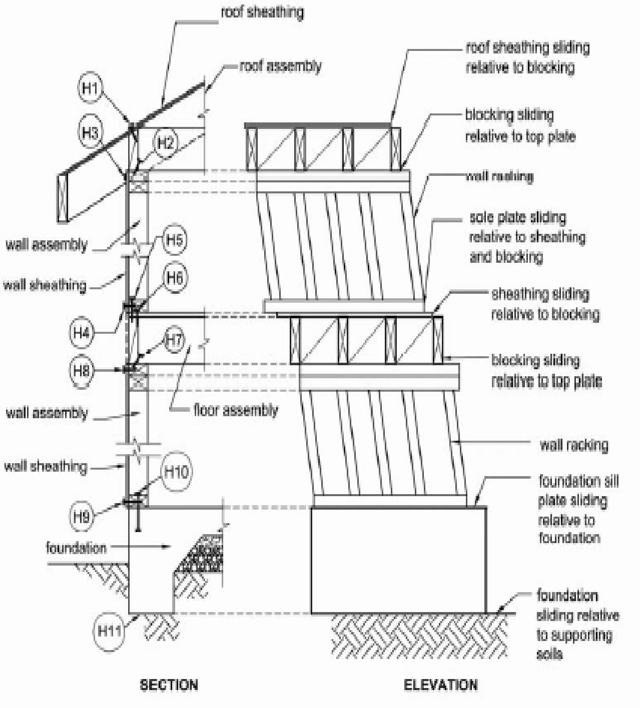


Fig. 2-6, Horizontal load path connections and deformations.

Load Path Connection for Overturning – Because the horizontal loads are applied high on the house and resisted at the foundation, overturning loads develop in the bracing walls. Figure 2-7 illustrates one possible load path for overturning loads. The left-hand side of the figure shows a wall elevation in which each of the "links" in the overturning load path is given a number, OV1 to OV8, corresponding to locations with uplift or downward loads due to overturning. The right-hand side of the diagram shows an elevation of the same wall that illustrates overturning deformations that will occur with earthquake loading from the left to the right. Uplift or tension occurs at one end of a wall simultaneously with downward force or compression at the other end.

The IRC only specifies connections (hold-down straps or brackets) to resist overturning loads for a limited number of

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bracing alternatives. The connectors used to resist horizontal loads in most IRC designs will be required to resist overturning loads as well as horizontal loads. This is a major difference between prescriptive design and engineered design in which resistance to overturning loads must be explicitly provided. The IRC requires use of hold-down devices in Section R602.10.6 for alternative braced wall panels; in Section R602.10.11, Exception 2, for SDCs D1 and D2 when braced wall panels are not located at the end of braced wall lines; and in Section R703.7 when stone or masonry veneer is used. Figure 2-7 graphically depicts use of straps to resist overturning loads; however, overturning can be resisted by connections employing such other devices as bolts, nails, or hold-down brackets. Because different device types may deform differently under load, it is preferable to use the same type of device for an entire story level. Variations in connector type from story to story are acceptable. When considering overturning in an engineered design, it is customary to include the effect of dead load (the actual weight of the house) in reducing uplift and overturning loads; however, this level of calculation detail is beyond the scope of the IRC provisions. Hold-downs should be provided wherever they are required by the IRC or recommended by this guide, irrespective of dead load.

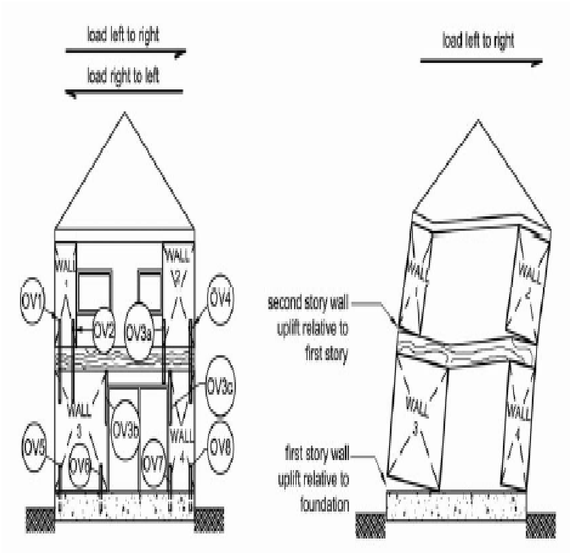

Fig.2-7, Overturning load path connections and deformations

System and Connection Strength and Stiffness Requirements – The roof-ceiling, floor, and bracing wall systems are the basic members resisting earthquake loads. Adequate earthquake performance of a house relies on:

- Adequate strength of roof-ceiling, floor, and bracing wall systems,

- Adequate stiffness of roof-ceiling, floor, and bracing wall systems to limit deformation,

- Adequate connection between systems to provide a functional load path, and

- Adequate connection to the foundation.

For most houses, it is generally anticipated that bracing wall system behavior will have more influence on the behavior of the house than the roof-ceiling or floor systems. Further, it is anticipated that wall behavior at lower stories will generally be more critical than at upper stories due to larger earthquake loads. Accumulation of Loads in Systems and Connections – Wind and earthquake loads increase or accumulate towards the bottom of the house. This is particularly applicable to loads in the bracing wall systems and their connections for horizontal loads and uplift and downward loads due to wall overturning. For example, overturning connections must be sized to resist all of the loads generated above the connection location. In a two-story house, the second-floor uplift connection, such as OV1 in Figure 2-7, will need to resist loads from the second story. The first-story uplift connection, such as OV5 in Figure 2-7, will have to resist the uplift loads from the second story plus the additional uplift from the first story. It can generally be expected that OV5 will need to resist a load two to three times that resisted by OV1. Downward loads at the opposite ends of walls and horizontal loads accumulate similarly. Although this accumulation of load often is missed in design for wind and earthquake loads, it is important and should be explicitly considered when connections are being selected.

House Configuration Irregularities

A house's configuration (shape) significantly affects its response to wind and earthquake loads. This section discusses the concepts and the IRC provisions for irregular house configurations.

Ideal Earthquake-Resistant House Configuration – For earthquake resistance, the ideal house would have:

- A simple rectangular shape,

- Bracing walls distributed uniformly and symmetrically through the house,

- No large concentrations of weight,

- Bracing walls at upper stories located immediately above walls in stories below,

- Wall bracing lengths that increase in lower story levels compared to the story above,

- No split-levels or other floor level offsets.

A version of this ideal house is shown in Figure 2-8. This ideal configuration results in loads and deformations being uniformly distributed throughout the house, which permits resisting elements to contribute equally to earthquake resistance. With good distribution of bracing walls, earthquake loads can be resisted very close to where they are generated (by house weight), which reduces the need for transfer of earthquake loads through floor and roof systems to other portions of the house. This helps reduce the poor performance that often results when such transfers are required.

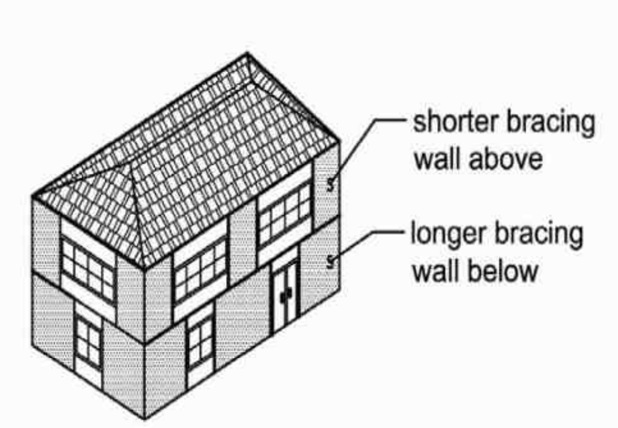

Fig. 2-8 ,Ideal building configuration for earthquake resistance.

Deviations from Ideal Configuration – Deviations from the ideal configuration are called configuration irregularities. As houses deviate from the ideal configuration, loads and deformations are concentrated, which causes localized damage that can result in premature local or even complete failure of the house. While the ideal configuration is attractive from the standpoint of earthquake resistance, houses with irregularities are much more popular and common than those without. Large open great rooms and walls of nothing but windows are examples of typical irregular configurations.

House Irregularity Concepts – House irregularities often are divided into two types: plan irregularities and vertical irregularities.

Plan irregularities concentrate earthquake load and deformation in a particular area of a house. A common cause is a center of mass (building weight) at a location different from the center of the resisting elements (bracing walls). This can be due to non-uniform mass distribution, no uniform distribution of bracing walls, or an irregular house plan. Two common examples are a house with one exterior wall completely filled with windows with no wall bracing provided (Figure 2-9) and a house with a large masonry chimney at one end. Houses with plan irregularities generally experience rotation in addition to the expected horizontal deformation. House rotation, as illustrated in Figure 2-10, magnifies the displacements, resulting in increased damage.

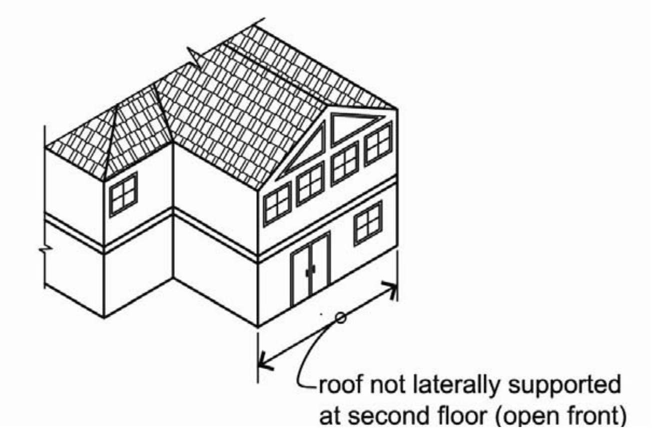

Fig. 2-9, Irregular building configuration with open front.

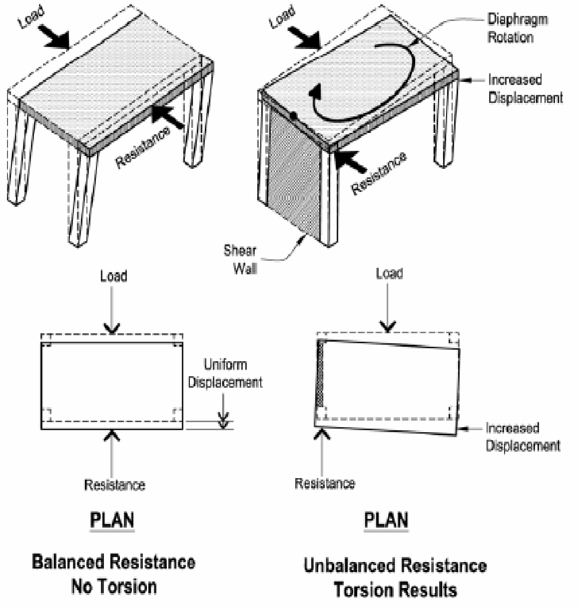

Fig. 2-10, Rotational response and resistance to torsion

Other common plan irregularities occur in T- and L-shaped houses that concentrate loads at the corners where the different wings of the house connect. Figure 2-11 illustrates the concentration of loads in an L-shaped house. The noted location of load concentration is where damage would be anticipated. Adequate interconnection of the house wings is required for good performance. Without additional consideration, poor performance and additional damage or failure would be expected for structures with such plan irregularities.

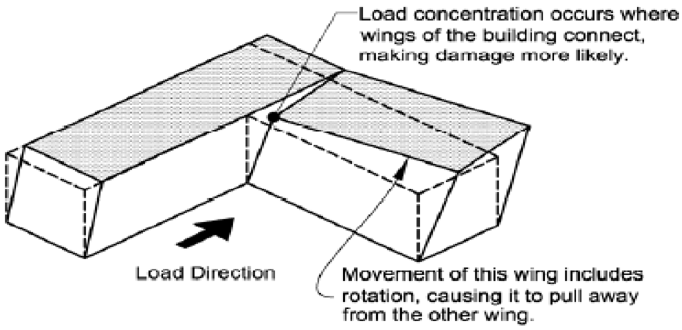

Fig. 2-11, Concentration of loads and possible damage and failure due to irregular plan

Vertical Irregularities – Vertical irregularities concentrate damage in one story of a multistory house. This occurs when the stiffness or strength of any one story is significantly lower than that of adjacent stories. If the displacements get large enough, they can cause complete failure of the soft story as illustrated in the configuration on the right.

The CUREE-Caltech Wood frame Project found that many two-story light-frame residential houses exhibit soft-story behavior to some extent because the first stories feature relatively large window and door openings and fewer partitions (less bracing) than the second stories where the bedrooms and bathrooms are located. Soft first-story behavior also was observed in the analysis of the model house used for this guide. Figure 2-14 provides an exaggerated illustration of deformation concentrated in the first story of the model house. Cripple walls around the perimeter of a crawlspace also can result in soft-story behavior. A weak story can cause damage or failure to be concentrated in that story if earthquake loading approaches the story strength.

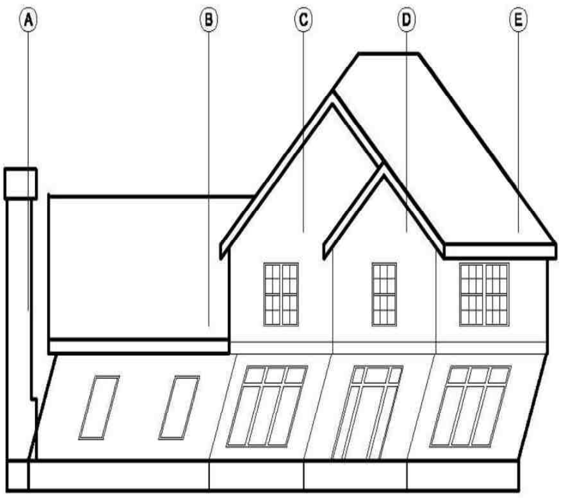

Fig. 2-14, Change in deformation patterns associated with soft-story irregularity.

Soft and weak stories, although technically different, can occur at the same time. Combined soft- and weak-story house irregularities have been the primary cause of story failure or collapse and earthquake fatalities in wood light-frame houses in the United States. To date, story failure has only been observed in houses that would not meet the current IRC bracing requirements or would fall outside the scope of the IRC.

IRC Approach to House Configuration Irregularities – The IRC incorporates two approaches to limitation of irregularities. The first and more explicit approach is found in IRC Section R301.2.2.2.2, which directly limits a series of irregular house configurations. Specific exceptions allow inclusion of less significant irregularities within IRC prescriptive designs. For one- and two-family detached houses, these provisions are applicable in SDCs D1 and D2.

The second and less obvious approach is the IRC requirement for distribution of wall bracing. Along with braced wall lines at exterior walls, interior braced wall lines must be added so that the spacing between wall lines does not exceed 35 feet per IRC Section R602.10.1.1 (adjustable to 50 feet by an exception) or 25 feet in SDC D1 or D2 per Section R602.10.11. Maximum spacing between braced walls in a braced wall line is also regulated. Houses perform better if the walls are distributed throughout, rather than concentrated in limited portions of the structure. This allows the earthquake load to be resisted local to the area where it is developed. Higher earthquake loads develop when loading must be transmitted to bracing walls in another portion of the house. Good distribution of bracing walls helps to mitigate the adverse effects of many irregularities.

Stepped Cripple Walls – IRC Section R602.11.3 provide specific detailing to reduce the effect of a concentration of load due to stepped concrete or masonry foundation walls. As illustrated in Figure 2-17, a direct tie to the tallest foundation segment provides uniform stiffness along the wall line.

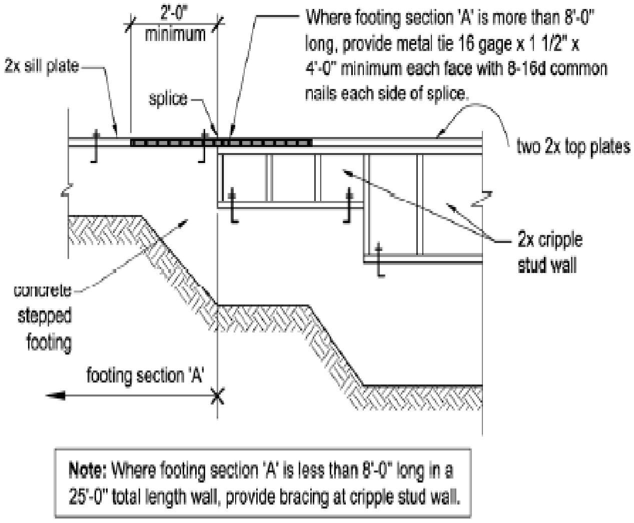

Fig. 2-17, Detailing required for stepped foundation walls (ICC, 2003).

Anchorage Of Home Contents

General

Anchorage of home contents can greatly reduce the risk of injury, property loss, and interruption of home use as a result of an earthquake. Anchorage is particularly recommended for large and heavy items such as water heaters, bookcases, and file cabinets and for items that could cause injury if they fell (e.g., items on shelves above a bed). Other priority items to anchor or otherwise restrain include wood stoves, similar heating appliances, and outside fuel tanks, all of which pose a fire risk.

Anchorage of other home contents will further reduce disruption following an earthquake. Measures to anchor computers and televisions range from very simple home fixes to specialized restraint systems available from a number of manufacturers. Locks on kitchen and china cabinets can help reduce the spilling and breakage of contents during an earthquake. Measures are available to secure a wide range of other home contents including pictures, mirrors, fragile objects, and fire extinguishers.

Securing Other Items

The examples included here show representative details for protecting common items from earthquake damage. Two different types of details are discussed:

•Do-it-yourself methods, which are simple generic methods for securing typical nonstructural items found in the home. Enough information is provided to permit a handyman with common tools and readily available materials to complete an installation.

•Engineered methods, which are schematic details showing common solutions for the items in question. These sketches do not contain enough information for installation; they are provided here primarily as an illustration of the scope of work required. The designation "Engineering Required" has been used for items where do-it-yourself installation is likely to be ineffective. FEMA 74 recommends that design professionals be retained to evaluate the vulnerability of these items and design appropriate anchorage or restraint solutions, particularly where safety is an issue.

Existing Houses

Additions or alterations can reduce the earthquake resistance of an existing house. With proper consideration, however, earthquake resistance can be maintained or even increased as part of an addition or alteration. This chapter discusses the earthquake-resistance implications of additions and alterations and provides recommendations and references for earthquake upgrades.

Additions And Alterations

Additions and alterations modify the load-resisting systems of existing houses. Generally, both the systems supporting gravity loads and those supporting lateral (wind and earthquake) loads are affected. For additions and alterations, IRC Section R102.7.1 requires that any new work conform to the IRC, but existing construction is allowed to remain unless it is made unsafe or will adversely affect the performance of the house. This wording provides significant opportunity for interpretation by the user and building official. IBC Section 3402 provides more specific guidance for acceptable reduction in strength or increase in loading, which may be appropriate to some additions and alterations. The following discussion of additions and alterations highlights issues and concerns that should be considered when interpreting IRC requirements.

Alterations

Alterations to existing houses often involve modification or removal of existing bracing walls and portions of floors and roofs. Figure 9-1 shows two alterations that remove exterior bracing walls from a house and disrupt the roof. Interior remodels often remove interior walls that provide bracing for earthquake and wind loads.

Where existing bracing walls are removed or reduced due to alterations, the remaining bracing walls should be checked for conformance with the bracing location, length, and bracing type requirements of the IRC provisions. The primary focus should be on bracing in the immediate vicinity of the alteration. If bracing deficiencies occur in other portions of a house, upgrade of those areas is encouraged.

When skylights, dormer windows, or similar openings are added to existing roofs, the openings should be checked for conformance with IRC requirements. For earthquake loading, this would include checking the opening size against permitted maximum sizes in the irregularities provisions and checking detailing against IRC requirements. The framing around the opening also should be checked for gravity load requirements such as doubled rafters and headers. If a significant rebuilding of the roof is occurring, a broader range of IRC provisions require checking as does the completeness of the load path for gravity and lateral loads.

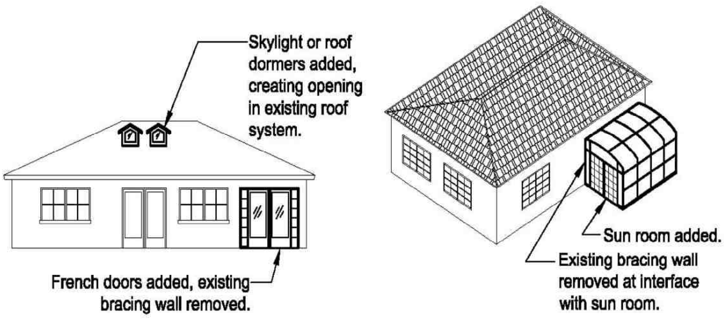

Fig. 9-1, Alterations to existing house: bracing wall and roof modifications (left) and modification for the addition of sun room (right).

Additions

An addition to an existing house often results in both the removal of some existing bracing wall, roof, and floor areas and the addition of weight and, therefore, increased earthquake loading. Most additions can be categorized as horizontal additions, vertical additions, or a combination of the two. Horizontal additions generally are built along the side of an existing house and often require reframing of the roof. Vertical additions generally involve the addition of an upper story. Figure 9-2 illustrates horizontal and vertical additions.

Horizontal additions may create irregularities or make existing irregularities worse. Thus, the IRC building configuration irregularity provisions should be reviewed to assess the post-addition configuration.

Horizontal additions include the construction of new bracing walls at the new exterior of the house (and sometimes on the interior). A significant reconfiguration of bracing walls at the interface of existing and new construction also often occurs. All bracing walls in the addition and interface should be checked for conformance with the IRC as should any portions of the existing house where framing and bracing modifications have been made.

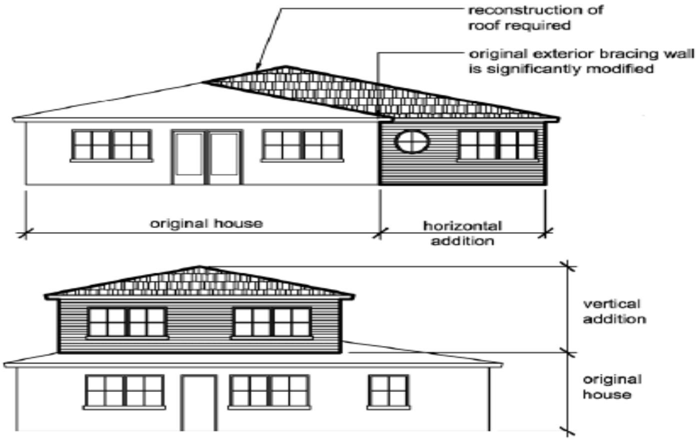

Fig. 9-2, Horizontal addition (above) and vertical addition (below).

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Finally, it is very important that the addition and the existing house be tied together very well. Ideally the level of interconnection should be the same as would occur if they had been built at the same time, but this generally cannot be practically achieved. Top plates and sill plates should be strapped between the new and existing construction to provide continuity.

Sheathing should be continuous and fastened to the same or interconnected framing members where possible. Where not possible, strapping of framing members should occur at a regular interval.

A vertical addition demands significantly greater consideration of both gravity and lateral (earthquake and wind) loads. This is because the story that is added often will more than double both the gravity and lateral loads on the existing lower story. Thus, when adding an upper story, the entire house, including the lower story, should be brought into conformance with current code requirements. With any addition or alteration, it is important that the gravity and lateral load paths be checked in detail to ensure that they are complete and meet the requirements of the IRC, IBC, or NFPA 5000. Additions and alterations often create nontypical load path details, and it is important that these details result in a complete load path with load-carrying capacity that is not less than would have resulted had typical details been used. In some cases, the new detailing deviates enough from that which is typical that engineered design should be employed.

Adding to or altering an existing house offers a clear opportunity to voluntarily upgrade existing portions of the house to better resist earthquake forces.

Earthquake Upgrade Measures

As noted elsewhere in this guide, the life-safety performance of houses in past earthquakes has been good with only a few exceptions. There are, however, certain conditions or portions of houses that have repeatedly resulted in earthquake damage, loss, and, in some cases, life loss or injury. Among these are:

•Missing or inadequate bolting to the foundation,

•Inadequate cripple wall bracing,

•Damage to bracing and finish materials,

•Excessive drift at garage fronts,

•Partial or complete collapse of hillside houses,

•Separation and loss of vertical support at “split-level” floor offsets, and

•Damage and collapse of masonry chimneys.

Because existing houses vary widely in configuration and construction based on age, region, siting, etc., it is necessary to identify upgrade measures appropriate to the particular house. In deciding on voluntary upgrade measures, take into account the configuration of the house and the potential benefit of the upgrade. Based on the principles discussed in this guide, some simple upgrade measures for existing houses are described below. This discussion addresses when the various upgrade measures are appropriate and suggests approximate levels of priority. If an upgrade is being undertaken on a voluntary basis, the house generally will not be required to conform to all of the code requirements for new construction. The building official or authority having jurisdiction should be consulted regarding minimum requirements. It is recommended that a basis for the upgrade work (i.e., published prescriptive method or earthquake load level) be established and clearly documented. When a house is being remodeled or extensively renovated, a systematic upgrade to meet the IRC requirements for new construction may be reasonable and may be required by the authority having jurisdiction.

The remainder of this section provides an overview of common upgrade measures.

Foundation Bolting

Many houses constructed in California before the 1950s and even later in other parts of the United States do not have anchor bolts that attach the wall bottom plate or foundation sill plate to the concrete or masonry foundation. During an earthquake, this can allow the wood framing to slide off the foundation, causing loss of vertical support and sometimes cripple wall or partial basement story collapse. Where the headroom and foundation configuration permit, this situation can be remedied by adding new anchor bolts. Adhesive anchors are recommended for use with unreinforced masonry or weaker concrete foundations but can be used with all foundation types. When anchor bolts are added, use of steel plate washers in accordance with the IRC is recommended.

If there is insufficient overhead room or the foundation configuration does not permit the use of anchor bolts, a wide variety of proprietary anchors are available from manufacturers. The primary purpose of this anchorage is to transmit horizontal earthquake loads acting parallel to the foundation from the foundation sill plate to the foundation. Where used, proprietary anchors should be designed for this use and loading direction by the manufacturer.

Cripple Wall Bracing

Cripple walls are partial-height wood light-frame walls that extend from the top of the foundation to the first framed floor. Cripple walls are very susceptible to damage during an earthquake but are also one of the easiest portions of a house to upgrade for improved earthquake performance. Many of the cripple walls of existing houses have inadequate bracing capacity due to the type of sheathing used, inadequate attachment of the sheathing, inadequate attachment of the framing to the foundation and first floor, or decay of the system.

Prior to an upgrade, the existing cripple wall system should be inspected and any sections of the framing that show signs of decay should be replaced. Framing materials in areas where moisture is present or in contact with the foundation should be replaced with preservative treated or decay-resistant materials. The upgrade should include anchorage of the foundation sill plate to the foundation, framing anchorage to the first-floor framing, and sheathing of the cripple walls with wood structural panel sheathing applied to either the exterior or interior face of the crawl space walls. Sheathing and connections may be installed to meet the requirements of the IRC or in accordance with other provisions developed specifically for upgrades. The basic elements of cripple wall bracing are illustrated in Figure 9-6.

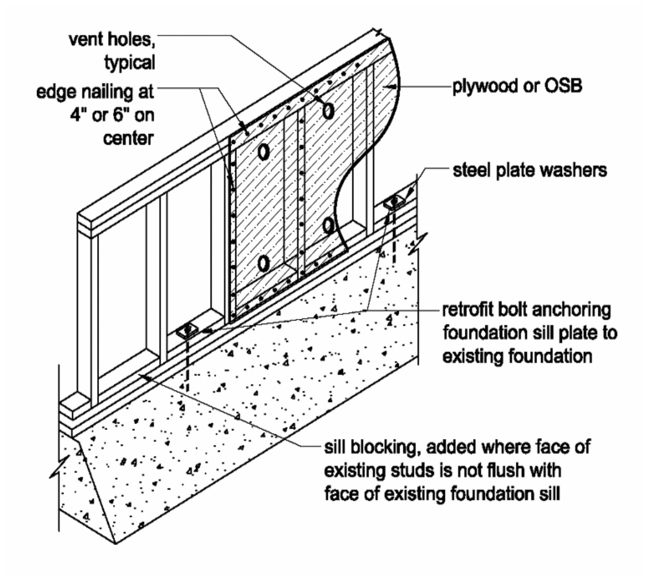

Fig.9-6 ,Cripple wall bracing.

Upgrade of interior cripple walls also is recommended where a crawl space is large. Where bracing is to be installed only at the perimeter of a large crawl space, performance can be improved by providing additional bracing length, reducing nail spacing from 6 inches to 4 inches, or providing sheathing on both faces of the cripple wall. A high priority is suggested for upgrading inadequately braced cripple walls based on the relatively low cost and generally high benefit.

Weak- and Soft-Story Bracing

Earthquake damage often is concentrated in the first story of multistory houses because the first story experiences higher loads while usually having the least amount of bracing. To reduce this damage, the first-story walls can be upgraded to increase their strength and stiffness. One method of accomplishing this is to remove the interior finish material (usually gypsum wall board or interior plaster) at the bottom of the wall in the corners of the house and to add hold-down anchors for overturning resistance. The anchors should be attached to the end studs (or other studs that have sheathing edge nailing) and the vertical rod or bolt should be attached to the foundation below. This upgrade does not require that the entire interior finish be removed but only a section in each corner that is one stud spacing in width and several feet in height. This is an effective upgrade measure where continuous reinforced foundations exist. Hold-down anchorage to isolated footings or unreinforced masonry footings is likely to be much less effective and engineering review is recommended.If the interior finish material is being removed for other reasons, then additional upgrade opportunities present themselves. These include additional anchorage of the top of the wall to the floor framing above, attachment of the bottom plate of the wall to the floor framing below, and the addition of blocking at the floor framing for the story above if not present at all locations that bear on walls. In addition, before gypsum wallboard or another finish material is attached to the walls, wood structural panel sheathing can be applied to the interior of the walls using 4-inch nail spacing around the perimeter of each sheet of sheathing and to the stud or post with the hold-down attached. A moderate priority is suggested for soft- and weak-story bracing upgrades in one- and two-family detached houses based on their moderate costs. The benefit can vary widely depending on the configuration of the existing house.

Open-Front Bracing

An open-front configuration occurs when bracing walls are omitted (or of grossly inadequate length) along one edge of a floor or roof. This is applicable to stories braced by light-framed walls. A number of apartment buildings with open front first stories were severely damaged or collapsed in the Loma Prieta and Northridge earthquakes. In this apartment building type, called “tuck-under parking,” significant lengths of first-story bracing wall were omitted in order to provide access to under-building parking. One- and two-family houses with open-front configurations also are vulnerable to earthquake damage. Two common occurrences of open-front configurations in one- and two-family houses are the fronts of attached garages with inadequate bracing length and window walls with no bracing. The open-front garage condition is of most concern when there is living space over the garage. In newer houses, narrow wall segments at the side of garage door openings may contain pre-fabricated bracing wall systems or engineered bracing walls that can be identified by the use of steel hold-down connectors or straps. Where there is no indication of such bracing systems, the installation of bracing is recommended. In detached one- and two-family houses, wood structural panel sheathing and anchorage connectors can be added in accordance with IRC provisions using adhesive anchors to existing foundations. The performance of narrow bracing walls with hold-down devices relies on the continuity of the existing foundation. If the existing foundation is not continuous, shows signs of damage or is constructed of unreinforced masonry or post-tensioned concrete, an engineering evaluation should be undertaken. Steel moment frames or collectors transferring loads to other portions of the house are alternative upgrade measures where use of bracing walls is not possible.A high priority is suggested for upgrade of open fronts in the first stories of multistory houses. A moderate priority is suggested in single-story houses or the top story of multistory houses.

Hillside House Bracing

A number of houses on steep hillsides collapsed or were severely damaged in the Northridge earthquake. Where damage occurred, the lot sloped downward from the street level, and the main floor of the house was located at or near street level with either a stilt system or tall wood light-frame walls between the house and grade. Many of the failures began with floor framing pulling away from the uphill foundation or foundation wall. There are no prescriptive upgrade measures currently available for these hillside houses so upgrade requires an engineered design. Upgrade measures to improve the response of the structure and

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reduce the amount of damage that occurs during an earthquake include:

• Securely anchoring the floor framing to the uphill foundation. This will require that anchors (i.e., hold-down connectors) be used to attach the floor joists to the foundation using adhesive anchors.

•Attaching the bottom plates of the framing of the stepped (or sloped) and downhill cripple walls to the foundations. Supplemental anchorage is particularly important where the top of the side foundations are sloped rather than stepped.

•Attaching the stepped or sloped side cripple wall top plates together at all splice joints using strap connectors. These straps should be heavy and connected securely to both sides of the splice, making the top plate of the stepped cripple wall act as though it were one piece along the entire length of the wall.

•Continuously sheathing the stepped wall and the down-hill wall with wood structural panel sheathing. Adequate shear transfer into and out of the cripple walls should be provided.

These upgrade measures should reduce but will not necessarily eliminate earthquake damage. A high priority is suggested for evaluation of hillside house vulnerability. The need for upgrade should be determined based on an engineering evaluation.

Split-Level Floor Interconnection

Split-level houses experienced partial collapse and significant damage in the 1971 San Fernando earthquake. These houses had vertical offsets in the floor framing elevation on either side of a common wall or other support. Earthquake damage occurred when sections of floor and roof framing pulled away from the common wall. The behavior of split-level configurations can be improved by adequately anchoring floor framing on either side to the common wall. Where offset floors are close enough in elevation that a direct tension tie can be provided between levels, an upgrade can be accomplished with installation of steel straps; a strap spacing of not more than 8 feet on center is recommended .Where direct tension ties are not practical, ATC (1976) provides a variety of details for anchorage of framing to the supporting wall. Finish removal will often be required in order to install connections, making this upgrade most practical when remodel work is occurring. It is difficult to establish a priority for this upgrade because significant damage was observed only in the San Fernando earthquake and photos suggest that the houses damaged had little or no positive connection provided between offset floor levels.

Anchorage of Masonry Chimneys

Fireplaces and chimneys in new construction it was noted that masonry and concrete fireplaces are heavy, rigid, brittle, and very susceptible to earthquake damage. IRC requirements for new construction in SDCs D1 and D2 dictate use of horizontal and vertical reinforcing and anchorage of the chimney to the framing at floors, ceilings, and roof. Chimneys on existing houses generally are even more vulnerable than new chimneys because they seldom have reinforcing or are anchored to the house. Common chimney failures range from hairline fractures of masonry and flue liners to complete fracture (i.e., the top of the firebox and at the roof line) permitting large sections of the chimney to fall away from or into the house, shattering into a pile of rubble.

The upgrading of chimneys is very controversial within the earthquake engineering community. Upgrading of existing masonry chimneys most often includes strapping the chimney to the house at the roof, ceiling, and floor levels. Where the chimney extends a significant distance above the roof line, braces from the top of the chimney down to the roof also may be added. Advocates of chimney bracing believe that anchoring the chimney will reduce the hazard posed by falling portions of the chimney. Opponents note that even with strapping, a chimney seeing significant earthquake loading is likely to be damaged to the point that removal and reconstruction are required. Both arguments deserve consideration and the reader is referred to the reference list for additional discussion. Where chimneys occur at the house exterior, steel straps similar to those discussed can be wrapped around the outside of the chimney and anchored to floor, ceiling, and roof framing in much the same way as was illustrated for new construction. Because this strap will have exterior exposure, heavy steel should be used and corrosion protection will need to be maintained. Although the addition of straps is not likely to keep a chimney from being damaged, it may reduce the falling hazard if it is damaged. A recommended alternative is removal of the chimney or fireplace and chimney and replacement with a factory-built fireplace and flue surrounded by light-frame walls.

Anchorage of Concrete and Masonry Walls

Under earthquake loading, concrete and masonry walls can pull away from roof and floor framing. This is primarily a concern where bolted ledgers support framing and no direct anchorage of the wall to the framing exists. This condition can be effectively upgraded by providing a tension connection between the wall and the floor and roof framing. The connection should be made to the joists when the joists run perpendicular to the wall and should be made to blocking and extend at least 4 or 5 feet into the interior of the floor system when the joists run perpendicular. An engineering evaluation of the existing condition and engineered design of upgrade measures are recommended.

III. ANALYSIS OF THE MODEL HOUSE

A model single-family detached house was developed and analyzed in preparing this guide. This appendix provides additional details concerning the model house, the analysis, and the interpretation of analysis results.

The analysis of the model house provided an approximate comparison of performance for varying wood light-frame house and bracing configurations permitted by the IRC and permitted the assessment of improved performance resulting from application of the above-code recommendations made in this guide. While the model house and the analysis performed cannot represent all houses that may be constructed using IRC provisions, they do provide a specific example of relative performance from which trends can been observed.

A1 Model House

The model house contained both one-story and two-story portions, three bedrooms, 2-1/2 baths, and an area of approximately 2,500 square feet plus garage. The house design is intended to reflect current configurations for wood light-frame construction but not necessarily any specific region of the United States. Separate analytical models were developed for common variations in the design including base conditions, exterior finishes, and earthquake bracing configurations.

The base conditions are slab-on-grade construction with turned-down footings (Figure A-1), continuous exterior footings with level 2-foot-high cripple walls (Figure A-2), a hillside condition with cripple walls of varying height (Figure A-3), and a full basement with concrete or masonry walls (Figure A-4). Exterior finishes are categorized as light and veneer. The light finish is intended to represent low-weight finishes such as vinyl or fiber-cement board siding. The veneer is intended to represent a single-wythe anchored brick veneer used for the entire house exterior. Bracing requirements were determined for each configuration and Seismic Design Category (SDC) in accordance with the 2003 IRC. Chimneys of light-frame construction were used for all house configurations.

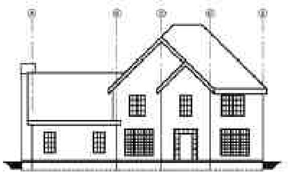

Figure A-1 Slab on grade base.

Figure A-2 Level cripple wall base.

Figure A-3 Hillside base.

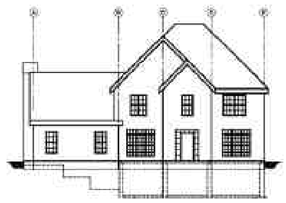

Figure A-4 Basement.

IRC prescriptive bracing requirements were determined for each combination of base condition, exterior finish, and Seismic Design Category. Because use of veneer is not permitted on houses with cripple walls in SDC D1 and D2 (IRC Section R703.7, Exceptions 3 and 4), both the level and hillside cripple wall configurations with veneer were limited to SDC C. The remaining spreadsheets used in determining bracing requirements for each of the designs are not included here due to their length; however, they and other information used in the analysis are available upon request from the Building Seismic Safety Council. Because gypsum wallboard is used in almost every U.S. residential building, it was used for the structural bracing wherever possible. Since it would be installed as a finish anyway, its use for bracing has the least construction cost. Wood structural panel wall bracing was used where length and percentage bracing requirements could not be met with gypsum wallboard. Alternative braced wall panels conforming to IRC Section R602.10.6 were used for the slender walls at the house front and garage front for slab-on-grade and basement base conditions. The alternative braced wall panels require support directly on a continuous foundation; therefore, they could not be used in combination with cripple walls. The IRC Section R602.10.5“continuous structural panel sheathing” modifications to bracing length and percent were not used. Several interpretations of IRC requirements were made in developing the bracing designs. First, it was recognized that the roof-plus-ceiling assembly weight would fall just below the limit of 15 psf of IRC Section R301.2.2.2.1 if the roof assembly weight were considered based on the unit weight on slope (12:12 roof slope) but would exceed 15 psf if the weight were adjusted to horizontal projected area. Although adjustment to the horizontal projected area is common practice in engineering calculations, it was decided that this calculation is not specifically noted in the 2003 IRC provisions so the roof-plus-ceiling assembly weight was deemed to fall within the 15 psf IRC limit.

The second interpretation related to the use of gypsum wallboard bracing (IRC Section R602.10.3, Method 5). IRC Section R602.10.4 requires that gypsum wallboard braced wall panels applied to one side of a wall be at least 8 feet in width. It was interpreted to mean that a continuous length of full-height wall not less than 8 feet wide would have to be available in order to use this bracing method. Interruption of the 8-foot length by perpendicular walls was interpreted to mean that it was not permitted. Where an 8-foot length of full-height wall was not available, wood structural panels were used as bracing instead. Based on this interpretation and the configuration of the model house, wood structural panels rather than gypsum wallboard were used for a significant portion of the exterior wall bracing. Where gypsum wallboard bracing can be applied to both faces of a wall (such as at interior walls), the minimum required length of full-height sheathing is reduced to 4 feet. While the perforated shear wall method that includes hold-down anchorage at the ends of the wall line was used as an above-code option for the analysis, the continuous sheathed option of IRC Section R602.10.5 that allows a 10 percent reduction in the sheathing percentage was not used in the analysis.

The third interpretation relates to the bracing requirements used for the model house in SDC C. IRC Table R602.10.1 specifically identifies sheathing length requirements for SDC C. The resulting bracing configurations are illustrated on a set of bracing plans and elevations for each of the designs are available from the Building Seismic Safety Council on a CD-ROM. The increased bracing length requirements for higher Seismic Design Categories can be observed to have reduced allowable door and window openings.

A2 Analysis Using Standard Engineered Design Methods

Prior to evaluation using other methods, earthquake forces and deformations were estimated using the linear static methods commonly used in engineering design of new

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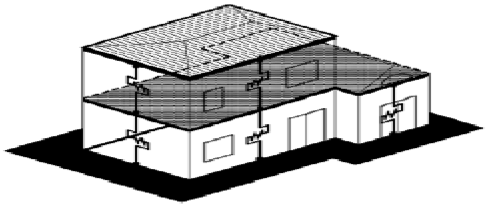
buildings. Included were force calculations using the International Building Code (IBC) linear static method, estimation of drift using the APA-The Engineered Wood Association four-term shear wall deflection equations at strength level forces, and amplification to estimated drifts using IBC amplification factors. This approach resulted in the APA shear wall deflection equations being used outside of their intended range (based on force per nail limits included with nail slip variables). This provided clearly unrealistic shear wall deflections amplified to unrealistic estimated drifts (over 36 inch drifts in some cases). Thus, it was concluded that the use of these engineered design estimates as predictors of performance for non-engineered buildings was not realistic and it was not pursued. Likewise, use of other available deflection equations that represent simplifications of the APA equations were not pursued. This issue should not occur when using this standard deflection calculation method for engineered buildings.

A3 Analysis Using Nonlinear Methods

Nonlinear time-history analysis using the Seismic Analysis of Wood frame Structures (SAWS) analysis program was chosen as the best available method for estimating force and deformation demands based on analytical studies that were verified against shake table results from the FEMA-funded CUREE-Caltech Wood frame Project. Analysis models included both designated bracing and finish materials. The Wood frame Project analytically predicted forces and deflections compared favorably with shake-table results and were clearly differentiated from analysis and testing results without finish materials (Folz and Filiatrault, 2002).The SAWS analysis program uses rigid diaphragms to represent floor and roof diaphragms. Walls are modeled as nonlinear springs with hysteretic parameters developed specifically to describe the behavior of wood frame bracing systems. For the example house, rigid diaphragms were used to represent the high roof, the low roof plus second floor, and, where appropriate, the first floor. Ten sets of hysteretic parameters were developed from component testing data to describe wall bracing and interior gypsum wallboard finishes. Figure A-6 illustrates the meaning of the parameters. For each of the bracing materials (with the exception of No. 5 and 6), the hysteretic parameters were determined for a 4-foot bracing length. Because widely varying lengths are used in the house, the parameters were scaled for varying bracing lengths.



Hysteretic parameters currently available from laboratory testing of wall components vary based on wall boundary conditions, test set-up, and test protocol. Parameters chosen for the analysis of the model house tended towards lower bounds of strength and stiffness. In order to simplify interpretation of analysis results, the analysis model uses consistent identification of bracing walls across all building configurations. Because of this modeling approach, cripple walls have been included in the model for all building configurations; where slab-on-grade construction occurs, the cripple walls are modeled as extremely rigid elements resulting in negligible deflection. In addition, some wall elements occur only in limited configurations; a bracing length of 0.1 foot is used where a bracing panel is intended to have no effect. The strength and stiffness contribution of exterior wall finishes was not included in the analysis. This approach was chosen because it would lead to a lower bound and, therefore, conservative estimate of deformation demand. In addition, some exterior finish materials are believed to have very little impact on building behavior (e.g., vinyl siding) and information was not available on the contribution of some other finishes (e.g., brick veneer). Due to the judgment necessary to select appropriate component testing and to derive parameters and the simplification of not including exterior finishes, the resulting modeling must be qualified as being approximate.

Earthquake demand is represented using the larger horizontal acceleration record from Canoga Park for the 1994 Northridge, California, earthquake. The ground motion scaling used for this analysis represents the demand used as a basis for code design. The demand from the maximum considered earthquake (MCE) ground motion (MCE) would be approximately 50 percent greater.

Detailed assembly weights and building weights have been determined for each house configuration. The analysis model spreads the resulting mass uniformly over a single rectangle used to describe each above-ground diaphragm. The center of the mass rectangle is set at the calculated center of mass of the building. This simplification, made necessary by analysis limitations, should have a minor effect on results.

A4 Analysis Results

The selected ground motion was run once in the horizontal X-direction and once in the horizontal Y-direction for each combination of base condition, exterior finish, and Seismic Design Category as well as for a series of above-code recommendations. From the nonlinear time-history analysis, peak drifts in each of the bracing wall lines and peak reactions to supporting foundations were extracted and summarized in tables. The “controlling” value was the largest absolute value of the X- and Y-directions.

A4.1 Deformation Demand Relation to Performance

In order to translate the results of the analysis into an approximation of house performance, three ranges of peak transient wall drift and associated approximate descriptions of building performance were developed. The choice of range and description of performance are based on component and full-building test results combined with the opinions of those participating in the development of this guide.

The approximate performance categories and corresponding drift ranges are:

•Minor damage potential – Less than or equal to 0.5% story drift

The house is assumed to suffer minor nonstructural damage such as cracked plaster or gypsum wallboard and hopefully would be “green-tagged” (occupancy not limited) by inspectors after an earthquake, which would permit immediate occupancy. Some repairs should still be anticipated.

- Moderate damage potential – Above 0.5% to 1.5% story drift

The house is assumed to suffer moderate damage including possible significant damage to materials and associated structural damage, but the building is assumed to have some reserve capacity in terms of strength and displacement capacity. The house hopefully would be “green-tagged” or, more likely, “yellow-tagged” (limited occupancy) by inspectors after an earthquake and may or may not be habitable. Significant repairs should be anticipated.

- Significant damage potential – Greater than 1.5% story drift

The house is assumed to have significant structural and nonstructural damage that could result in its being “red-tagged” (occupancy prohibited) by inspectors after an earthquake. Significant repairs to most components of the building should be anticipated, and it may be more economical to replace the house rather than repair it.

Use of these three categories permits an approximate comparison of the relative performance of different IRC bracing solutions and above-code recommendations.

IV. DISCUSSION OF RESULTS

In most cases, the drift increased with increased SDC in spite of the bracing requirements also having increased. The approximate performance often increased from minor or moderate to significant as the SDC went from C to D2. The primary reason is the inclusion of interior gypsum wallboard in the models for all Seismic Design Categories. As the SDC increased, interior walls became required braced wall panels per IRC requirements rather than simply nonstructural partition walls; however, the analytical model did not change because the interior walls had already been included. The result was application of a higher demand to a model with only nominal increases in resistance. Although the building mass increased significantly with the addition of brick veneer, the increase in drift ranged from moderate to slight. This is due to the IRC requirement for wood structural panel sheathing and hold-down devices for veneer in SDCs D1 and D2. The analysis model differentiated between wood structural panel shear walls with and without hold-down devices so the different strength, stiffness, and deformation capacity were accounted for. Because of this, the IRC bracing required for brick veneer was seen to partially compensate for the increased demand. The above-code measures were applied to the slab-on-grade base condition. The measures were seen to generally reduce the building drift, although drift increases were seen in a few walls due to changes in diaphragm rotation. In SDC D2, the approximate performance was improved by one category for all three above-code measures. In SDCs C and D1, significant decreases in drift were seen within an approximate performance category. The cost of implementing each above-code measure during construction of the house was estimated in terms of percentage change to the construction cost for the basic house structure. Comparison to total house cost was not made because variations in finishes and fixtures can dramatically vary the house cost.

V.CONCLUSIONS

Use of continuous wood structural panel wall sheathing (fully sheathed) with overturning anchors in the corners of the house significantly reduced the drift in all Seismic Design Categories, and the approximate performance category was increased by one in SDC D2. The cost of making this change was estimated to be 9 to 10 percent of the cost of the structural portion of the model house used in this guide. The addition of hold-down anchors at the ends of each full-height wall segment (at the corners and edges of each door and window) significantly reduced the drift in all Seismic Design Categories, and the approximate performance category was increased by one step in SDC D2. For the model house, the cost of implementing this improvement was estimated to be 18 percent of the structural cost of the house.

Lapping wood structural panel wall sheathing over the band joist of the floors did not have a significant effect in SDC C or D1 but did improve the approximate performance category by one in SDC D2. The cost of implementing this improvement was estimated to be 0.5 percent of the cost of the structural portion of the house. This above-code measure can be accomplished by either sheathing the wall with oversized panels (9-foot panels on an 8-foot wall) or cutting and blocking standard size sheets. Use of the above-code measures in combination is thought to have a cumulative effect in improving performance and so is encouraged. The population of India has doubled since the last great Himalayan earthquake in 1950 (M8.6). A repeat of this largest intra-continental earthquake in recorded history, would be really devastating with untold misery and loss of human life. The capital cities of Bangladesh, Bhutan, India, Nepal, and Pakistan and several other cities with more than a million inhabitants are vulnerable to damage from future earthquakes originating in the Himalaya. In view of above the earthquake risk management policy of the country has become proactive to motivate earthquake-prone community by devising social, technical, administrative, political, techno-legal, techno-financial forces for a concerted, long-term effort to change, improve, and accelerate the enactment and implementation of cost-effective public policies for mitigation, preparedness, emergency response, and recovery and reconstruction.

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