# STUDY REPORT

## SR 262 (2011)

# Guidance for Bracing Design for Hillside Houses

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## Preface

The guidance here is to clarify critical structural issues in carrying out bracing design, especially seismic design, of hillside LTF houses; and to develop a rational bracing design method for hillside LTF houses. The guidance was developed based on the current NZBC and the current New Zealand Design Standard AS/NZS1170.


## Acknowledgments

This work was jointly funded by the Building Research Levy and the Ministry of Science and Innovation.


## Note

This report is intended for structural engineers and building consent authority professionals.

# Guidance for Bracing Design for Hillside Houses

## BRANZ Study Report SR 262


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## Reference

Liu, A.A., 2011. *Guidance for Bracing Design for Hillside Houses. Study Report 262*. BRANZ Ltd. Judgeford, New Zealand.

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# 1. INTRODUCTION

## 1.1 General

In New Zealand, residential houses are usually light timber framed (LTF) buildings and they are constructed according to “NZS3604”, which is an acceptable solution to New Zealand Building Code Clause B1 Structure and the application of NZS3604 is limited to regular buildings up to 10m high on flat sites.

More and more residential houses in New Zealand are built on hillside sites. The main difference between hillside houses and houses within NZS3604 scope lies in the subfloor bracing systems. Subfloor frame systems of hillside LTF houses can vary significantly, depending on site and construction techniques. Often the subfloor frame structures have a mixture of different structural forms and could be founded at different levels. As a consequence, hillside LTF houses often have severe vertical and horizontal irregularities, and their structural design is outside the scope of NZS3604.

The bracing design of hillside houses under wind action has no dynamic effects and it is clearly much simpler than the bracing design for seismic action. Once the wind design action is determined based on the Loading Standard, the rest of the bracing design for wind should be similar to seismic design. Hence the following discussions focus on the engineering characteristics of hillside houses under seismic actions.

Seismic responses of building structures are determined by many building characteristics, such as, building configuration and geometry, the interaction of the foundation structural (subfloor system) systems with the superstructures, so on. Response of subfloor frame systems of hillside houses to ground motion and interaction of the subfloor frame systems with the superstructure could significantly alter the building performance, leading to very different seismic response, in comparison with buildings within NZS3604.

For hillside houses, different site conditions often have different subfloor construction techniques. Hillside LTF houses can be divided into two categories: up-slope houses and down-slope houses. Up-slope houses are on ground that rises above the street and down-slope houses are built on ground that drops below the street. Construction techniques of subfloor frame systems, which are part of the structures, are often very different for these two types of hillside LTF houses. As a consequence, the engineering characteristics of these two types of hillside houses could be very different from each other.

There is no guidance available for seismic bracing design of hillside timber framed houses in New Zealand. Therefore, bracing design methods used can vary significantly from design to design, creating greater difficulties for design engineers to demonstrate design compliance to the building consent authority (BCA), meanwhile the BCA checkers have no guideline to use to establish the compliance of a structural design with the Building Code.

The guidance developed here is to clarify critical structural issues in carrying out bracing design, especially seismic design, of hillside LTF houses; and to develop a rational bracing design method for hillside LTF houses. The guidance was developed based on the current NZBC and the current New Zealand Design Standard AS/NZS1170.

## 1.2 Scope

This guidance provides the fundamental philosophy for carrying out rational bracing design, particularly EQ design, of hillside LTF houses where significant stiffness incompatibility exists. The principles presented can be also applied to other situations where significant stiffness/deformation incompatibility exists.

In many ways the guidance only contains qualitative principles. Detailed information on the force-deformation capacity of any particular systems is not provided in this because of the huge variations in the used systems and in the application situations.

## 1.3 Limitations

The application of the proposed design guideline is limited to hillside light timber framed houses, which are not higher than 3 storey at any vertical plane, and no more than two storeys supported on timber framing, and the superstructure construction generally complies with NZS3604.

The design guideline only deals with the structural bracing design issues and it excludes other engineering issues, such as geotechnical engineering issues and site stability.

The intended users are structural engineers and building consent authority people.

# 2. CLASSIFICATIONS OF HILLSIDE LTF HOUSES

Subfloor frame systems are part of hillside LTF building structures and seismic performance of hillside LTF houses is significantly influenced by the construction techniques of the subfloor systems, depending on site situation. Based on site conditions, hillside LTF houses can be divided into two categories: up-slope houses and down-slope houses.

Design guidance of seismic bracing design of hillside LTF houses is presented in the following for different hillside LTF house categories, which are classified based on engineering characteristics of the subfloor frame systems.

Definition of seismic directions for hillside houses is graphically demonstrated in Figure 2.1.

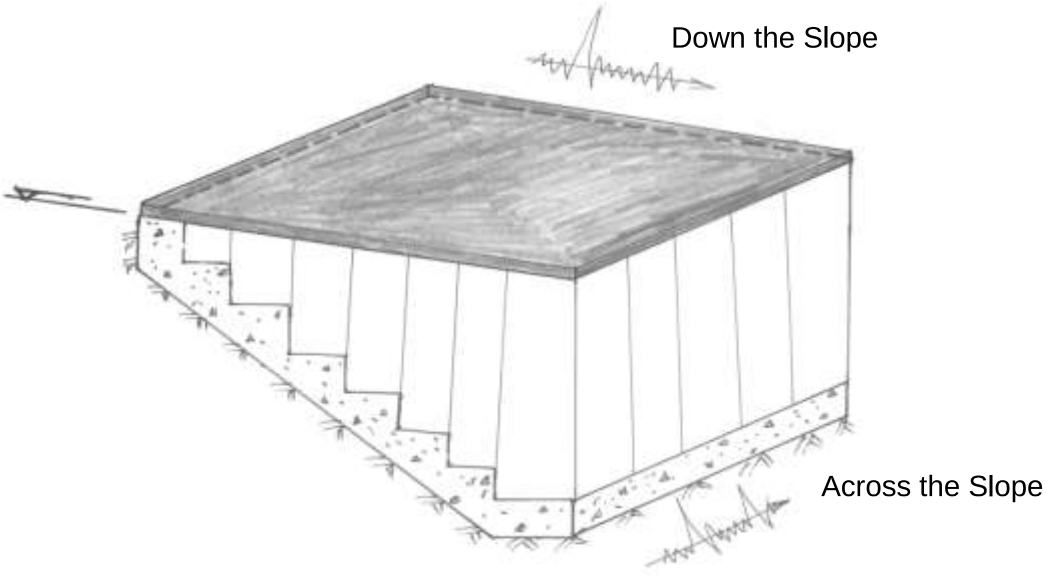



**Figure 2.1 Definition of Seismic Action Directions for Hillside Houses**

## 2.1 Up-slope LTF Houses

Up-slope LTF houses are constructed on the ground that rises above the street and their design and construction techniques often incorporates features necessary to have easy street access and minimise construction problems posed by the land rising above the street.

As a result, typical up-slope LTF houses are commonly built into the ground. Often the garage and secondary portions of the living space are built in excavations cut into the slope at or near street level and may incorporate retaining structures. The main living level is built at a level above the street, as low and as near to the street as practical on foundations which might be at different levels.

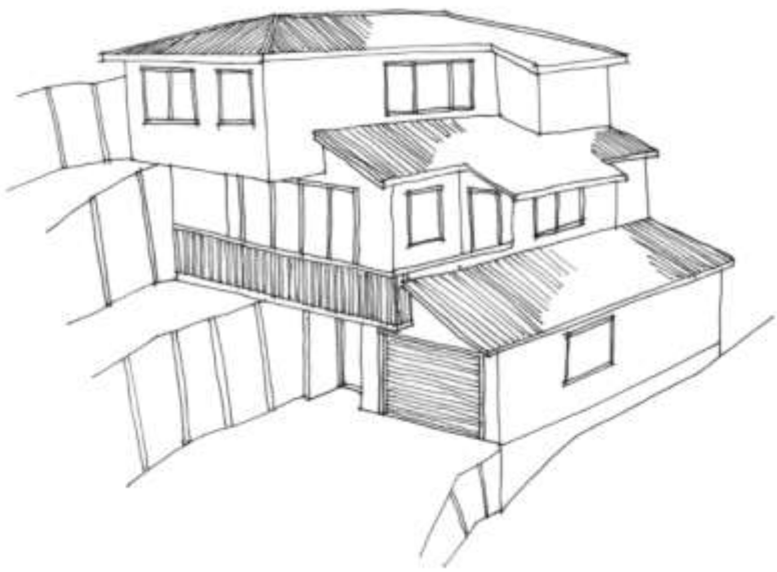
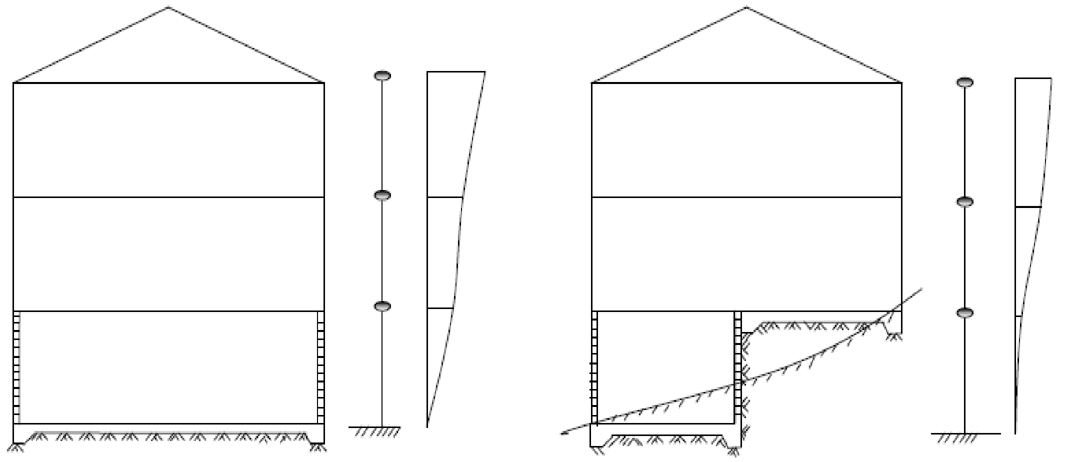


**Figure 2.2 One Typical Up-Slope House**

Figure 2.2 shows an indicative perspective view of a typical up-slope house. Figure 2.3 shows comparative engineering characteristics of an up-slope house with a house constructed to NZS3604.



House to NZS3604
Equivalent Static Method ✓
Ductility Assumed=3.5

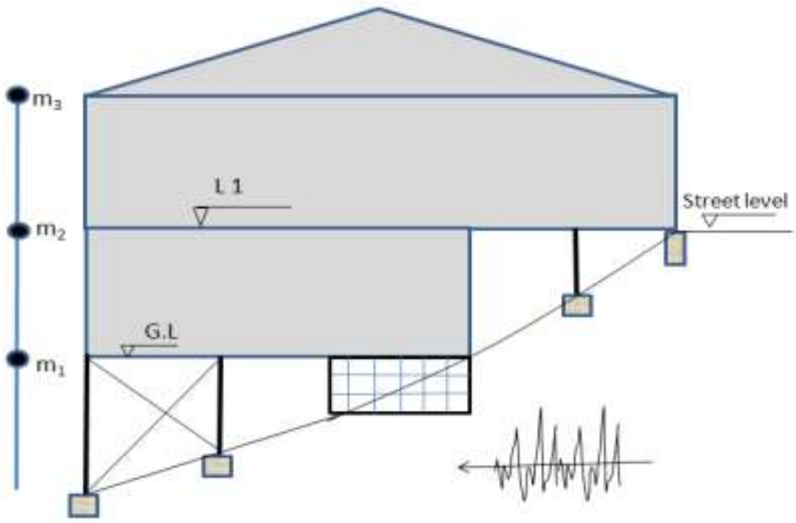
Up-Slope House
Equivalent Static Method ✓
Ductility Capacity is similar to NZS3604

**Figure 2.3 Conceptual Comparison of Up-Slope Houses with Houses to NZS3604**

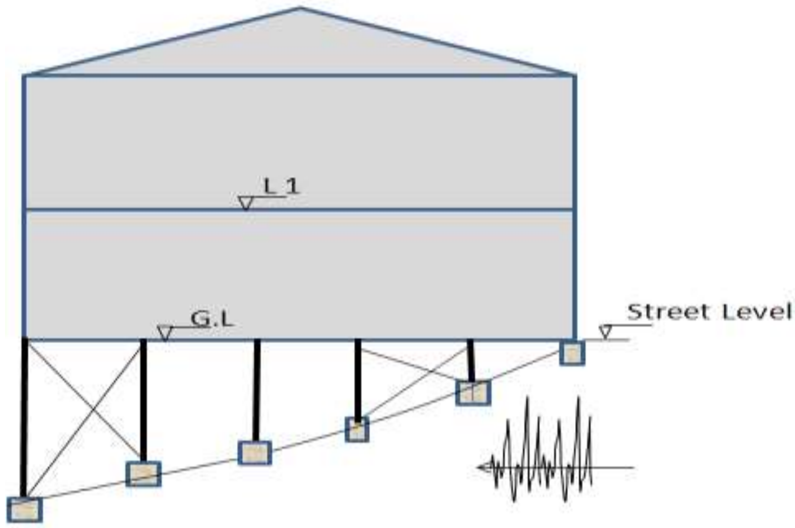
## 2.2 Down-Slope LTF Houses

Contrary to up-slope LTF houses, down-slope LTF houses could be supported by foundation beam(s) or retaining walls at different ground levels on near street side, and the rest of building is supported by substantial subfloor framing systems at different levels because they are built on ground that drops below the street, see Figure 2.4(a). Therefore down-slope houses can be further classified based on whether or not the bracing capacities are provided at different levels, see sections 2.2.1, 2.2.2.

As shown in Figure 2.4(b), stiffness incompatibilities in the subfloor frames always exist due to the nature of the sloping site. In addition, the subfloor bracing framing structure often consists of mixed subfloor bracing systems with varying stiffness properties as in Figure 2.4(a). This aggravates stiffness variation problem in subfloor frame systems and worsens the implications resulting from stiffness incompatibility, such as torsional response.




(a) Foundations at Different Levels




(b) Stiffness variation in Subfloors

**Figure 2.4 Different Subfloor Systems in Typical Down-Slope LTF Houses**

### 2.2.1 Down-Slope LTF Houses Anchored at Floor Levels

Down-slope LTF houses braced at floor levels refer to the situations where, apart from the subfloor frames, there are foundation beams/foundation walls at lower and/or upper floor levels and the building superstructure is adequately connected to the ground (perhaps by ground anchors or tie-backs).

This situation is graphically illustrated in Figure 2.5.

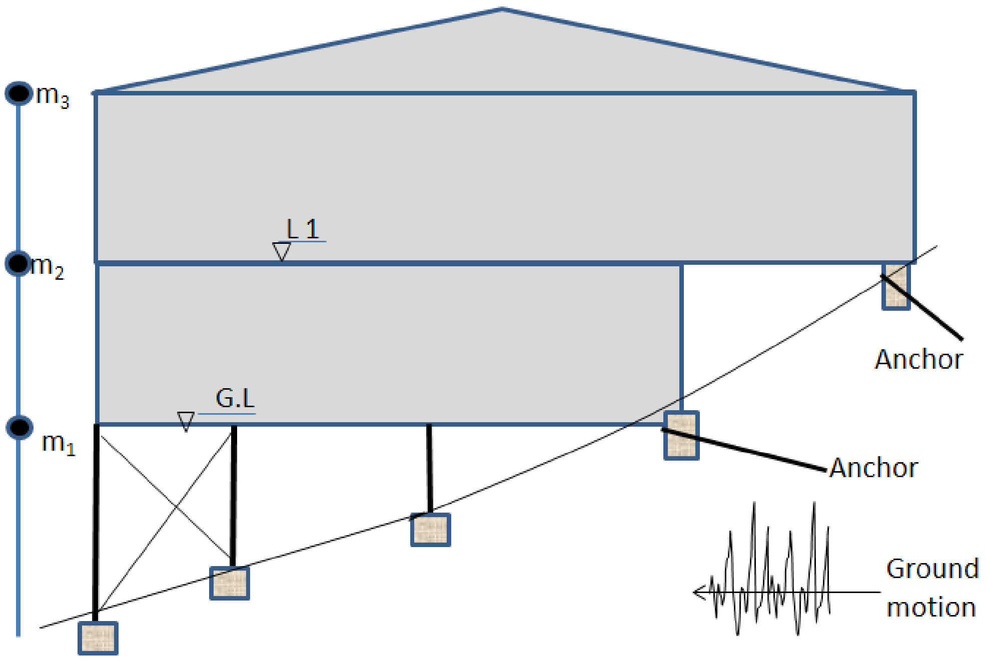



**Figure 2.5 Down-Slope LTF House Anchored at Floor Levels**

### 2.2.2 Down-Slope LTF Houses Not Anchored at Floor Levels

There are situations where down-slope LTF houses are not anchored at floor levels. For example, there are no adequate connections to the ground from buildings.

This situation is graphically illustrated in Figure 2.6.

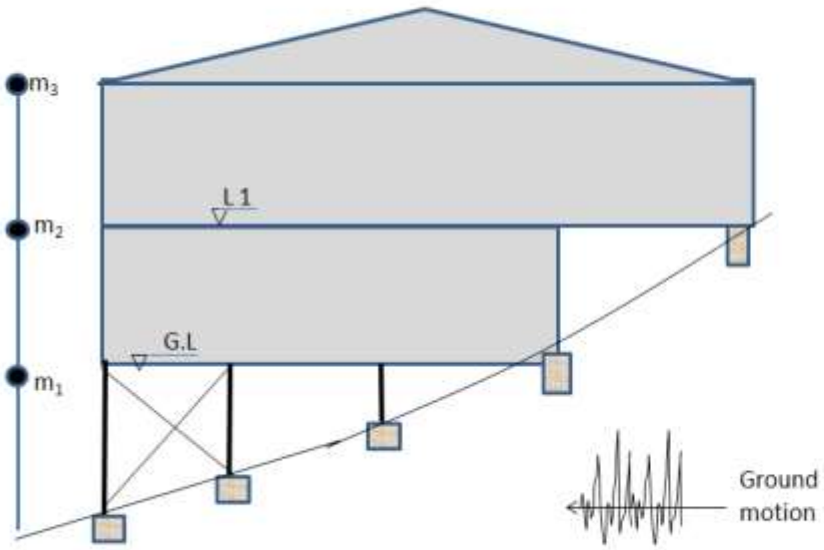



**Figure 2.6 Down-Slope LTF House Not Anchored at Floor Levels**

# 3. SEISMIC DESIGN OF TYPICAL UP-SLOPE LTF BUILDINGS

For up-slope LTF houses as classified in Section 2.1, which are founded immediately on ground, the fundamental period of the buildings is likely to be very short, less than 0.4s. According to NZS1170.5, the equivalent static method can be used for deriving seismic actions, similar to NZS3604. The potential failure mechanisms are similar to those assumed in NZS 3604, hence the wall bracing design of the buildings in this category can generally use NZS3604.

There are two critical issues associated with the hillside timber framed buildings in this category, which are beyond the scope of NZS3604. The two critical issues are the design of the uphill foundation walls (which are probably also retaining walls) and the connections from the building to the foundation walls.

It is common that the light timber framed superstructures are connected to the foundation beams/retaining walls at floor levels hence the seismic actions associated with the building weight will come to the retaining walls through the connections. It is important that the designers adequately estimate the seismic actions allocated to the foundation walls (which could be limited by either the connection capacity or the out-of-plane resistance of the wall) and then designs the foundation walls and the connections for the allocated seismic actions. This is especially important when the seismic action is down the slope. In this case, the uphill foundation walls/retaining walls could be subjected to the out-of-plane seismic actions associated with the building weight and the soil behind the wall. If there are stiff bracing systems (such as walls) present down the slope, the uphill foundation walls (retaining walls) will be relieved from being overloaded, otherwise the uphill foundation walls (retaining walls) could be significantly loaded due to the allocated seismic action from the building.

The designer could choose not to utilize the retaining walls in resisting the seismic actions associated with the building weight. In this case, the retaining wall design is no different from conventional standalone retaining wall design except that building weight will be imposed to the wall as a vertical gravity load, and the connections from the building to the walls should allow the building to slide over the walls and the seating needs to be enough to accommodate the expected movement.

Furthermore, the proper bracing arrangement is also necessary in order to prevent significant torsional response when the seismic action is across the slope. This can be done either by providing sufficient bracing capacity (across the slope) at the lower ground end, or by providing sufficient bracing systems at the ground level, which are far apart in the direction perpendicular to the seismic direction. The method is the same as conventional structural engineering design. In this case, a structural floor diaphragm needs to be provided.

# 4. DESIGN OF DOWN-SLOPE HOUSES ANCHORED AT FLOOR LEVELS

For hillside LTF houses in this category, the fundamental period is likely to be less than 0.4s for both seismic directions. Based on NZS1170.5, equivalent static method can be used in deriving the seismic actions.

## 4.1 Seismic Action is in Down the Slope Direction

**Step 1:** Determination of the seismic weight at each floor level, i, $m_i$.

Total seismic weight, Wt =g$\sum m_i$ .

**Step 2:** Determination of total seismic force action, $V_b$, based on AS/NZS1170.5.

Seismic coefficient, C, is determined by assuming that T1 = 0.4s, 5% damping and the displacement ductility of unity, $\mu$=2 (a limited ductile failure mode, so use ductility of 2 as for a single degree freedom system.

$V_b = C\ W_t$ (1)

Where: Wt is the total seismic weight and Vb is the total seismic action.

**Step 3:** Determination of the seismic force actions allocated to the foundation beams at upper and lower floor levels, $R_u$, $R_L$ as shown in Figure 4.2.

$R_u + R_L = V_b$ (2)

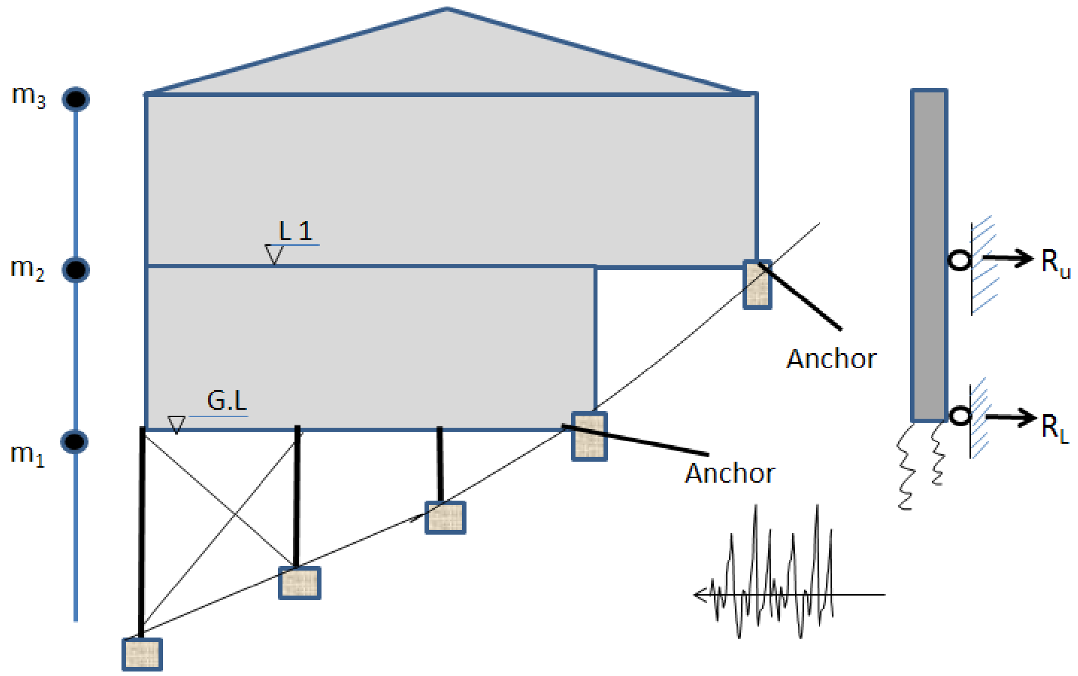



**Figure 4.2 Seismic Actions on the Buildings and on the Foundation Systems**

If the uphill foundation wall has sufficient out-of-plane capacity and the connections from the foundation beams/walls to the house are adequate, you can allocate the sum of the seismic actions at the roof level and at the upper floor level to the foundation beam/wall at the upper floor level and allocate the rest of the seismic action to the foundation wall/beam at lower floor level.

Namely,

$R_u = C(m_3+m_2)g$ (3)

$R_L = Cm_1 g$ (4)

This is simply illustrated in Figure 4.3.

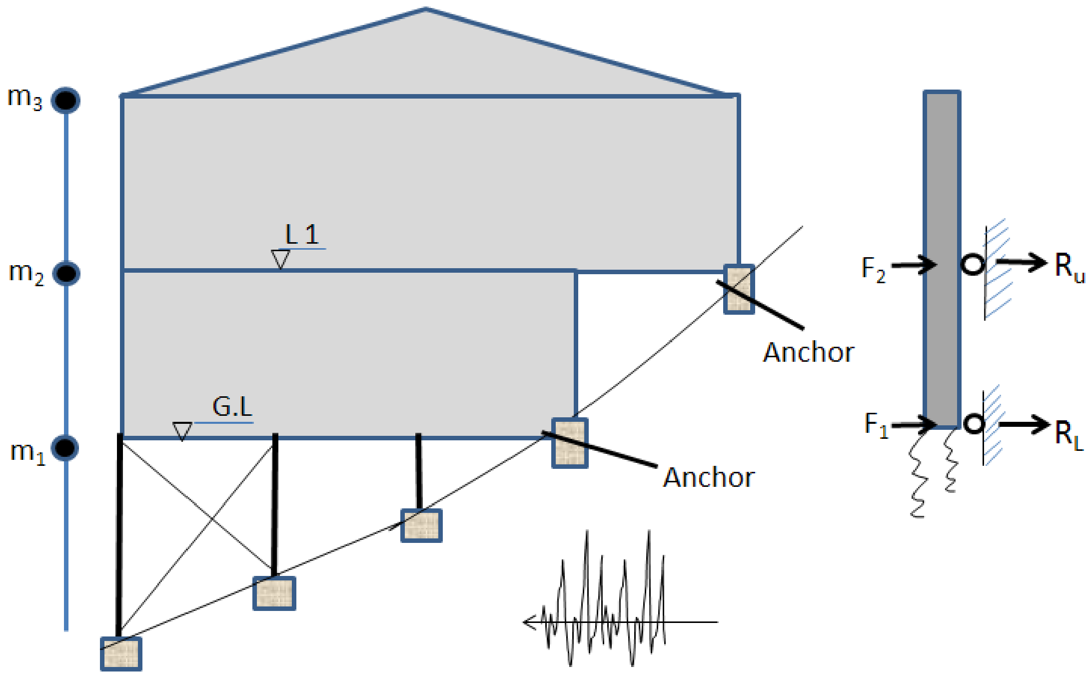



**Figure 4.3 Simplified Load Transfer Model**

**Step 4:** Design connections from building structure to foundation beams / walls.

For the connection design, the allocated design loads to foundation beams/walls need to be amplified, for instance by 1.5, to allow for the effects of the potential torsional responses as well as over strength.

The conventional connections used in house construction are unlikely to satisfy the required connection capacity. It is suggested that special bracket connections be developed and experimentally validated. The special bracket connection details could use the proprietary products, such as Bowmac products, and the development of these details is beyond the scope of this project.

**Step 5:** Design the foundation beam/wall at upper floor level for the combined out-of-plane action of the allocated seismic action, $R_u$, and the seismic soil pressure.

**Step 6:** Design the foundation beam/wall at lower floor level for the combined out-of-plane action as step 5, $R_L$ , if the foundation wall/beam is designed to be utilised.

It needs to be appreciated that the resolution of the out-of-plane actions imposed to the foundation beam/wall into the ground needs to be adequately considered and a **deep foundation** such as piles or ground anchors under the foundation beam/wall may be required. Without adequately designing the foundation beam/wall for the allocated seismic actions (out-of-plane), the superstructure could be jeopardised.

**Step 7:** Bracing design for the flexible subfloor frames in Down the slope direction.

As described above, the total seismic actions have been allocated to the foundation walls at upper and lower levels and there is no need for designing subfloor frames for lateral seismic actions. Also it is difficult to activate the flexible subfloor bracing frames when rigid connections between the building and the foundation beams/walls exist. Namely the anchors at floor levels will not work together with flexible subfloor frames.

However, a certain amount of bracing capacity should be still provided to the flexible subfloor framing systems in order to build the reasonable resilience into the subfloor systems. This is also essential because the torsional response resulting from across the slope seismic needs to be resolved by the lateral resisting systems in Down the slope direction.

The design action for the flexible pile groups is tentatively taken to be at least 30% total seismic demand.

$V_{\textbf{demand,subframe}} >= 0.3 * CW_t$ (5)

In modelling the subfloor systems, the subfloor braced frames across the entire subfloor in down the slope direction are lumped together by rigid links and they are all subjected to the same displacement magnitude, see Figure 4.4. From experimentally established force displacement curve for the flexible subfloor framing systems, the maximum capable displacement in subfloor framing systems for $V_{demand,subframe}$ can be estimated. As a guide, the calculated deflection should not be more than 35mm as assumed in NZS3604 for ULS.

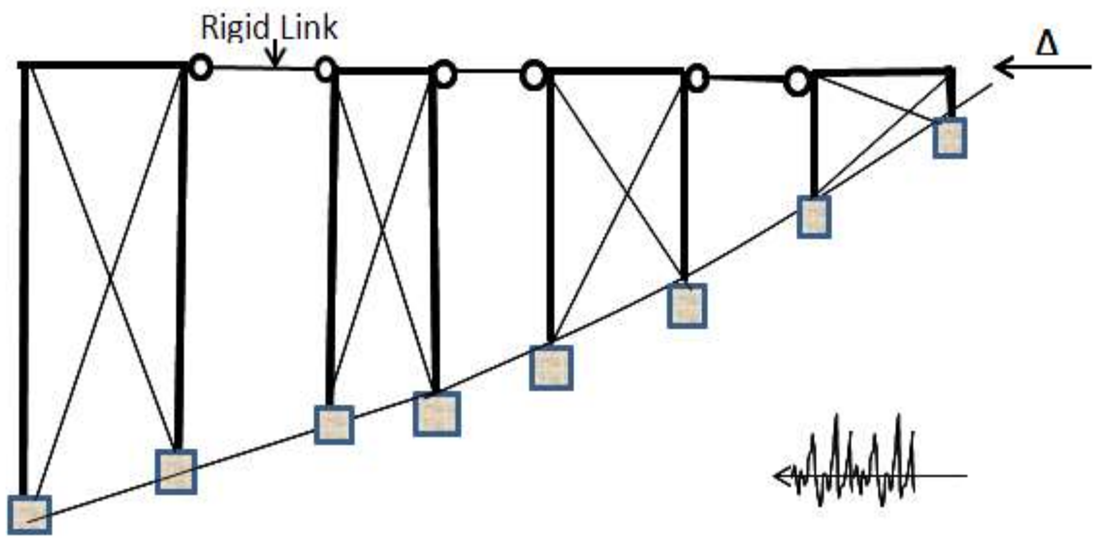



**Figure 4.4 Modelling of the Subfloor Braced Frames**

Figure 4.4 is somewhat like a conventional bridge subjected to longitudinal seismic actions. Progressive failure can potentially occur. It is recommended that the displacement-based design procedure be used here. That is, the sum of the force capacities of all the frames at one particular displacement magnitude is the force capacity of the entire subfloor system, and this, combined with the displacement magnitude, will be the seismic resistance of the entire system.

Detailed displacement – based procedure can refer to the procedure in Section 5.1, or use the displacement-based procedure as introduced in Displacement-Based Seismic Design of Structures by Priestley [Priestley, et al, 2007].

The subfloor braced frames should consist of at least two braced lines at edges and each brace line should have at least one flexible braced frame in this direction. The braced lines should be spaced at not more than 6m apart.

**Step 8:** Design Floor Diaphragms

The perimeter chords need to function as continuous members. Floor diaphragms should be designed as structural floor diaphragms, see NZS3603. Framing around openings (such as stairs) needs to be carefully detailed.

## 4.2 When Seismic Action is in Across the Slope Direction

Step 1: Same as step 1 in Section 4.1

Step 2: Same as step 2 in Section 4.1

Step 3: Same as step 3 in Section 4.1

Step 4: Design the foundation beams/walls for across the slope seismic actions

The upper and lower foundation walls, orientated across the slope, should be allocated to take the action $R_u$ and $R_L$ respectively. The foundation walls are mainly subjected to in-plane shear action in this case and they can be also subjected to out-of-plane action due to the torsional response resulting from the eccentric load resisting systems.

Usually the in-plane shear capacity of the foundation walls is sufficient and the connections from the superstructure building to the foundation wall are likely to limit the seismic actions resisted by foundation walls.

The specifically designed connections from the building to the foundation walls as described in step 4 of Section 4.1 need to be experimentally validated for the seismic resistance for the shear action in across the slope direction.

**Step 5:** Bracing design for the flexible subfloor frames in Across the slope direction

Significant torsional response would be expected when the building is subjected to across the slope seismic because of the significant differences in the stiffness of the different subfloor frame systems as shown in Figure 4.5. Typically the foundation walls are very stiff but the braced pile groups are likely to be very flexible, especially the outmost external ones at lower ground end.

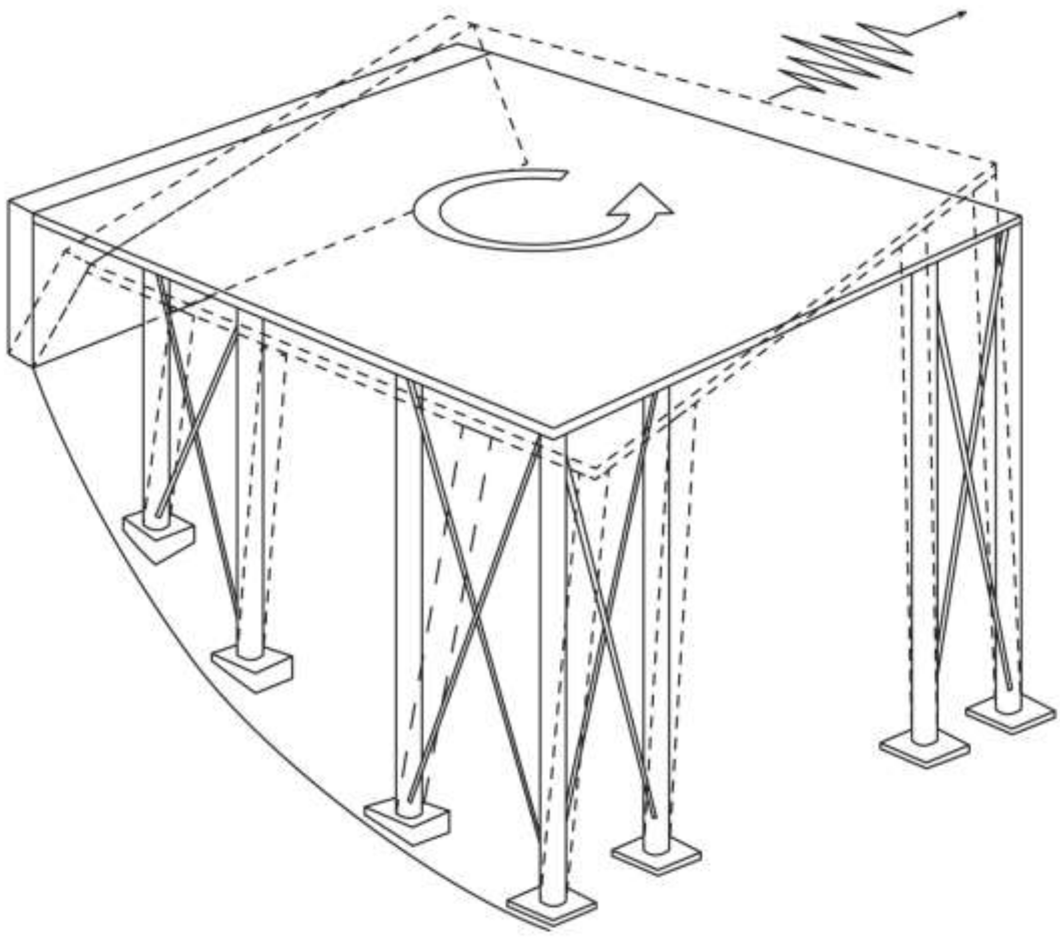


**Figure 4.5 Torsional Response (Foundation Wall is Adequately Connected to Floor)**

The very stiff nature of the foundation wall in comparison with the braced pile group means that the two systems won't be activated at the same time and the total reliance on the foundation beams potentially induces significant torsional response, so the lateral load resistance in down-the-slope direction should be provided.

To reduce the torsional response, certain amount of bracing capacity should be still provided to the flexible subfloor framing system in across the slope direction even the total seismic actions are allocated to the foundation walls at floor levels.

The design action for the flexible pile groups is again tentatively taken to be at least 30% total seismic demand determined before.

$V_{d,subframe} = 0.3CWt$ (5)

The modelling technique for the subfloor frames across the entire subfloor system assumes the same translational displacement magnitude for all the frames.

## 4.3 Wall Bracing Design – Anchored at Floor Levels

It is recommended that the bracing design of the walls for the superstructures of the hillside buildings in this category can use NZS3604 because the structural deformation profile is similar to the light timber framed buildings directly founded on the ground.

# 5. SEISMIC DESIGN OF DOWN-SLOPE LTF BUILDINGS NOT ANCHORED AT FLOOR LEVELS

In any of the following circumstances, the subfloor structure can be considered as having no anchorage at floor levels and the total seismic actions need to be transmitted to the ground by the subfloor framing systems. The procedure described in this section can then be used.

(1). Foundation beams/walls provide gravity supports only;

Or

(2) Foundation beams/walls are not designed to take the out-of–plane actions;

Or

(3) The building structure has no foundation walls.

Figure 5.1 shows a generalised model of the hillside houses in this category where the subfloor structure consists of braced pile groups only. Other subfloor framing structural systems should follow similar principles because, in either case, the subfloor framing systems consist of many frames of varying stiffness/dynamic properties and therefore they could reach their ultimate limit state at different displacements. It is crucial to prevent the progressive failure in a major seismic event.

It is suggested that the direct displacement-based procedure be used in designing the subfloor frames of this nature and this will better overcome the progressive failure issue associated with a mixed system of different stiffness.

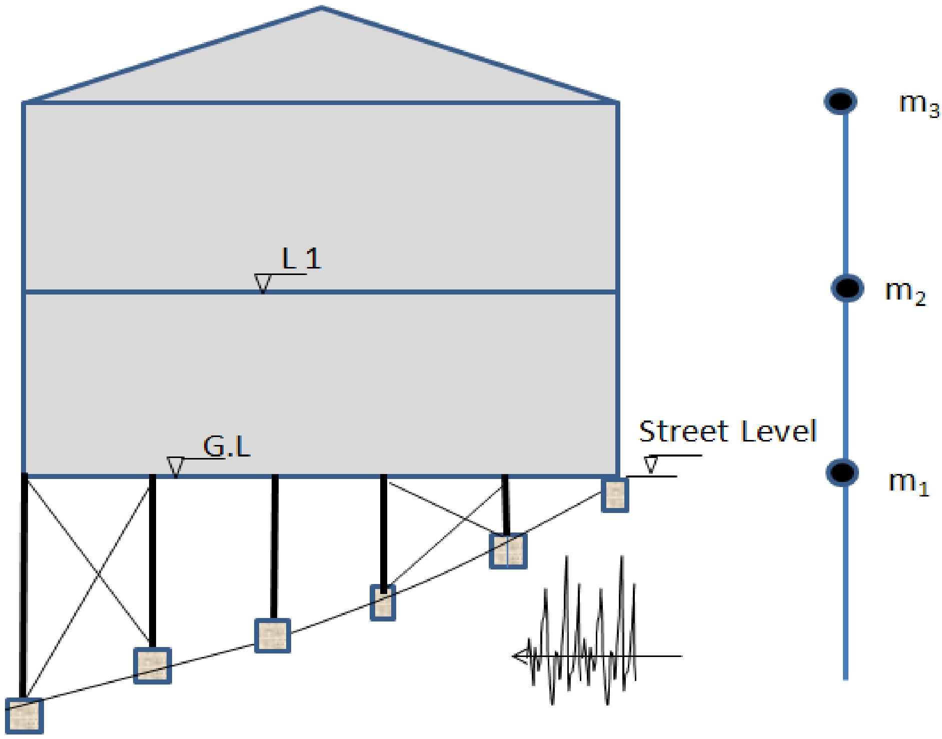



**Figure 5.1 Buildings Founded by Subfloor Frames Only**

## 5.1 Bracing Design of Subfloor Systems for Down the Slope Seismic Actions

For down the slope seismic actions, the seismic performance of the subfloor frames in a major earthquake is similar to the seismic performance of a bridge with piers of varying heights or stiffness when the bridge is subjected to seismic actions in the longitudinal direction.

The proposed procedure is based on a direct displacement-based philosophy and it is described in general as follows:

**Step 1:** Determine the total seismic weight

Total seismic weight of the building is the sum of $m_i$.

$$Wt = g \sum m_i \qquad (6)$$

**Step 2:** Determine a target displacement capability at the top of the subfloor framing system based on the subfloor structural system, $\Delta_{cap}$

The procedure is similar to step 7 of section 4.1 with all the subfloor braced frames lumped together by rigid links. The target displacement capability, $\Delta_{cap}$, is limited by the stiffest system and should be reasonably assessed based on the experimentally validated load-displacement curves of different systems.

**Step 3:** Determine the load capability, $V_{cap}$ , of the subfloor bracing system, $V_{cap}$ at the attainment of the displacement $\Delta_{cap}$ , see figure 5.2.

From experimentally established force displacement curve for the subfloor framing systems, the force capacity, $V_{cap}$ , of the subfloor bracing frames corresponding to the determined displacement, $\Delta_{cap}$ , is determined.

$$V_{cap} = V_A + V_B \qquad (7)$$

**Step 4:** Determine the effective stiffness $K_{eff}$

$$K_{eff} = \frac{V_{cap}}{\Delta_{cap}} \qquad (8)$$

**Step 5:** Determine the effective period using $T_{eff}$

$$T_{eff} = 2\pi\sqrt{\frac{m_{eff}}{K_{eff}}} \text{ where } m_{eff} = 70\%\ m \qquad (9)$$

**Step 6:** Determine the seismic demand, $V_{demand}$, corresponding to $T_{eff}$ for the appropriate soil class (most likely to be "B" to NZS1170.5) and damping of 5%

**Step 7:** Compare $V_{demand}$ with $V_{cap}$ to make sure that $V_{cap} > V_{demand}$

**Step 8:** If $V_{demand}$ is significantly lower or higher than $V_{cap}$, iterate the process until condition $V_{cap} > V_{demand}$ is satisfied.

**Step 9:** Design the ground floor diaphragm as structural diaphragm, refer to NZS3603

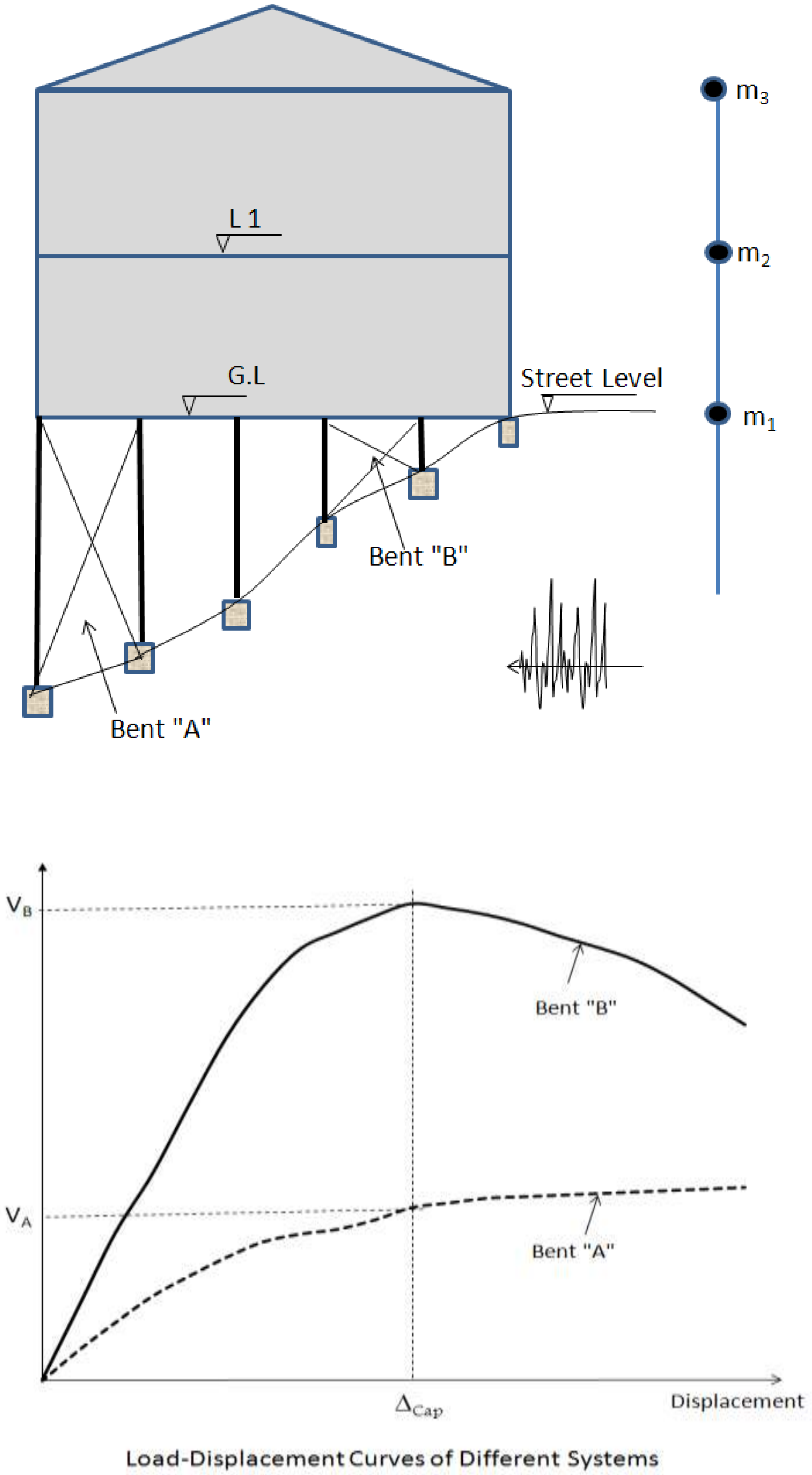



**Figure 5.2 Determination of Load Capacity of Different Subfloor Structures**

## 5.2 Bracing Design of Subfloor Systems for Across the Slope Seismic Actions

Similar to the design for Down the slope seismic, the bracing design of the subfloor framing systems can use the displacement-based procedure and only the braced subfloor frames are relied on.

**Step 1:** Determine the total seismic weight

**Step 2:** Determine the deformation capacities at ultimate limit state for the entire subfloor framing system, $\Delta_{design}$. This indicates that all the subfloor bracing systems need to deform at similar magnitudes to avoid significant torsional response.

**Step 3:** Design the subfloor bracing system based on the specified design deformation target, $\Delta_{design}$. The displacement-based procedure as described in Section 5.1 shall be followed.

## 5.3 Wall Bracing Design – Not Anchored at Floor Levels

The bracing walls of the superstructures of the light timber framed hillside buildings in this category should be designed based on the displacement based procedure as for the subfloor frame design.

The wall bracing demand is derived, based on the effective period derived from Equation (9), damping ratio of 5%, limited ductility, say $\mu = 2.0$.

# 6. SEISMIC DESIGN OF DOWN-SLOPE LTF HOUSES WITH MIXED SUBFLOOR SYSTEMS

In designing the subfloor bracing frames for buildings on mixed subfloor systems, the design philosophy is the same as for the subfloor frame design stated in Section 5 because the design principles of the subfloor systems as shown in Figure 5.1 and Figure 5.2 have allowed for the potential characteristics of the varying stiffness in the subfloor systems.

It is suggested that all the different subfloor systems in the considered direction be lumped together by rigid links (see step 7 in Section 4.1) and the total lateral load resisting capacity is estimated based on the experimentally established force-displacement curves for each system. The combination of the force capacity, $V_{cap}$, of the entire system and the corresponding displacement capacity $\Delta_{cap}$ gives the final seismic capacity of the entire system.

On this basis, the effective stiffness, $K_{eff}$, and the effective period, $T_{eff}$ , can be derived using the displacement based procedure. Then the seismic demand, expressed as $V_{demand}$, corresponding to $T_{eff}$ and 5% damping can be determined from NZS1170.5. See Section 5.1.

The derived seismic demand, $V_{demand}$, is compared with the estimated capacity, $V_{cap}$. If $V_{demand}$ is significantly lower or higher than $V_{cap}$, revise the design and iterate the design process until $V_{cap} > V_{demand}$ is satisfied.

Again, the ground floor is to be designed as a structural diaphragm, refer to NZS3603.

# 7. GUIDELINES FOR WIND DESIGN

The wind design of the hillside houses is much simpler than the seismic design.

In detail, the entire building is to be divided into blocks when the bracing demand and the bracing capacity are calculated for either direction of the seismic events when designing the subfloor frame structure and foundation beams/walls for hillside houses. In dividing the entire building, the division should be along the locations of changing elevation levels and /or along the changing location of the floor plans.

For each block, the wind design action can be derived based on NZS1170. For each design block, the bracing capacity is provided accordingly as for seismic design.

# 8. REFERENCES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