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Computer Simulation of Torsion on a Timber Framed Building with Horizontal Irregularity

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Preface

This report presents the results of a computer simulation study to quantify the extent that torsion will increase expected maximum wall deflections when New Zealand houses, with plan irregularity, experience earthquakes. Vertical irregularity is not covered in this report.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for standards committees, structural engineers, architects, designers and others researching earthquake resistance of houses.

COMPUTER SIMULATION OF TORSION ON A TIMBER FRAMED BUILDING WITH HORIZONTAL IRREGULARITY

BRANZ Study Report SR 171 (2007) **SJ Thurston**

REFERENCE

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ABSTRACT

This report presents the results of a computer simulation study to quantify the extent that torsion will increase wall deflections when New Zealand houses, with plan irregularity, experience earthquakes. Vertical irregularity is not covered in this study.

Houses were modelled in a non-linear computer package and subjected to time history earthquake loading. The floors and ceilings were modelled as rigid diaphragms. The walls were modelled as springs with load/deflection characteristics matched to wall test measurements. The maximum wall in-plane earthquake-induced deflections were plotted against the eccentricity of house mass.

It was found that houses with bracing wall layouts which only just met the minimum requirements of NZS 3604 may twist and deflect excessively. An alternative distribution of bracing elements in houses to limit torsional demand was proposed. This was found to be suitable.

It is recommended that a further study be done to investigate the torsional performance of construction complying with NZS 3604, but with the emphasis on vertical rather than horizontal irregularity. The effect of non-rigid floor diaphragms also needs to be considered.

KEYWORDS

Torsion, twist, New Zealand houses, horizontal irregularity, vertical irregularity, computer simulation, bracing distribution.

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1. INTRODUCTION

1.1 Current house bracing wall design procedure in New Zealand

Most New Zealand houses are designed and constructed using the non-specific design procedures in the New Zealand standard for Timber Framed Buildings, NZS 3604:1999 [1]. They generally use light timber framed walls having a variety of wall sheathing and fastening systems. Typically, manufacturers of wall bracing products have their systems tested using the BRANZ P21 [2] test method. The results are evaluated and wind and earthquake bracing ratings assigned. Designers use the manufacturers' published ratings to ensure new house designs have sufficient lateral bracing to meet NZS 3604 wind and earthquake demand loads.

NZS 3604 (SNZ 1999) was derived using the loadings in NZS 4203 (SNZ 1992). However, the requirement for the analysis to consider accidental eccentricity of floor mass of ±0.1B, where B is the plan dimension of the floor at right angles to the direction of loading, was not fully implemented in NZS 3604 as described in the two paragraphs below.

NZS 3604 specifies wall bracing to be located as close as possible to corners of exterior walls and evenly throughout the building, although leaves the application of this vague. It introduces the concept of interior wall bracing lines which are lines of interior braced walls. Unless a specifically constructed diaphragm is used, interior bracing lines between exterior walls must be at a maximum of 6 m centres in both directions. Bracing elements are required to be evenly distributed along each line as far as possible.

To minimise torsional effects and reduce the stress within horizontal diaphragms, NZS 3604 requires exterior walls to have a minimum bracing rating of 10 BU's/m (= 0.5 kN/m), and interior bracing lines to have a minimum bracing rating of 70 BU's (3.5 kN). These minimum requirements were not increased when NZS 3604 changed from working stress to limit state design in 1990, or when bracing demand was increased in 1999. This suggests that the magnitude of current values of minimum wall strength is likely to be too low. In addition, the torsion provisions also have the following deficiencies:

1. The values do not relate to the magnitude of the house bracing demand forces i.e. do not increase for houses with heavy roofs/walls, houses in high earthquake zones, or for two as against one storey construction.

2. For internal walls the minimum strength is not a function of house geometry i.e. is the same for small and large houses.

This report examines the effectiveness of the NZS 3604 provisions to ensure houses have good torsional resistance.

1.2 Proposed alternative torsion provisions

The writer proposes that NZS 3604 adopts the following minimum bracing distribution requirements for houses that do not use specifically constructed diaphragms.

"Each bracing line shall have a bracing capacity not less than the greater of:

1. The value obtained from Tables 5.5 to 5.7 multiplied by a length of 2 m; and

2. The value obtained from Tables 5.8 to 5.10 multiplied by both a length of 2 m and the building width at the bracing line.

This is a tributary area approach which assumes that the walls on each bracing line carry 2 m width of averaged house loading, which is effectively 1 m either side of internal walls. This approach does not have the basic deficiencies noted above.
For houses with low demand loads, the writer's criteria will often be less severe than the current NZS 3604 provisions. For high demand load situations, the writer's criteria is expected to improve the torsional response.

This report examines the effectiveness of these proposed provisions to ensure good torsional resistance will be achieved.

1.3 Recommendations of minimum bracing rating for walls below floor diaphragms

Special minimum bracing distribution provisions are made in NZS 3604 for construction using specifically constructed "floor diaphragms". Such construction and distribution criteria were not analysed in depth in this report, but is described below for completeness. However, a proposed revision to the bracing provisions for such construction is also given below and a cursory justification given. A more in-depth examination may show these proposed changes themselves need modification.

Section 5.4.2.2 of NZS 3604 allows areas of a building to have no internal bracing lines if the floor or ceiling above is constructed as a "diaphragm". These are usually large areas and may indeed encompass the entire house. (Actually, NZS 3604 needs amending to clarify that it is only for walls below, not above, the diaphragm.)

Section 5.6.2 of NZS 3604 gives the minimum bracing rating for walls on edges of diaphragms. For buildings with diaphragms it is recommended that the provisions of NZS 3604 still apply except that the words "10 bracing units/m" be replaced with "0.25xEQxLxD for earthquake design and 0.25xWLxD for wind design, where D is the diaphragm width perpendicular to the wall under consideration and L is the diaphragm length". EQ is the earthquake demand values in Tables 5.8 to 5.10 and WL is the wind demand values in Tables 5.5 to 5.7 of NZS 3604.

It is also recommended that the minimum value of 100 BU's for walls bounding diaphragms be increased to 200 BU's. In addition, it is recommended that the sum of the bracing resistance of walls bounding a diaphragm be no less than EQxLxD for earthquake design and WLxD for wind design for the two building main axis directions.

An example is given in the paragraph below to illustrate the effectiveness of these proposed changes.

The forces on a stand-alone diaphragm for an earthquake force, F, are plotted in Figure 1. If the left hand side wall is the weakest to meet the proposed provisions then it will have a strength of 0.25F. Therefore the right hand wall will have a strength of 0.75F. The combination of the applied load, F, and the resistance of the two side walls gives a residual torque of 0.25xFxD. If the top wall is the weakest to meet the proposed provisions then it will also have a strength of 0.25F. Therefore the resisting torque from the top and bottom walls = 0.25xFxL. Thus, a balance is achieved if 0.25xFxD = 0.25xFxL (i.e. if L = D). Hence, for this example the proposal will only be able to provide a balance if D>L. However, it is still an improvement on the status quo.

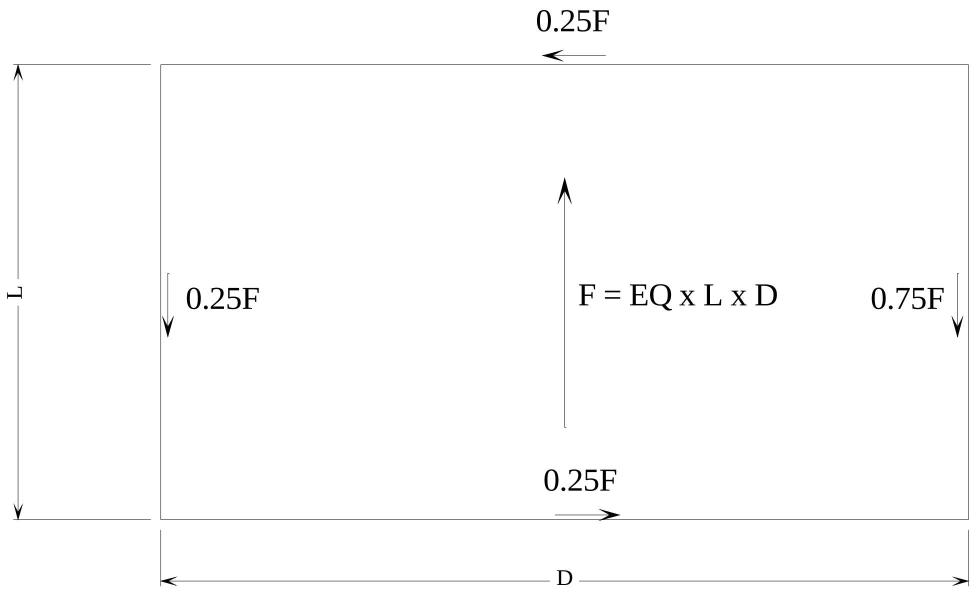


Figure 1. Maximum forces for the proposed bracing requirements for walls under diaphragms.

1.4 Project overview

This report presents the results of a computer simulation study to quantify the extent that torsion will increase wall deflections when New Zealand houses, with plan irregularity, experience earthquakes. The houses analysed were assumed to have effective diaphragms at each floor level but these were not taken to be the special construction discussed in Section 1.3.

Houses were modelled in a non-linear computer package and subjected to time history earthquake loading. The floors and ceilings were modelled as rigid diaphragms. The walls were modelled as springs with load/deflection characteristics matched to test wall measurements. The maximum wall in-plane earthquake-induced deflections were plotted against the eccentricity of house mass from the house geometric centroid for each of:

- houses with bracing wall layouts which only just meet the minimum requirements of NZS 3604
- houses with bracing wall layouts which only just meet the minimum requirements described in the writer's alternative proposal (based on earthquake loading) given in Section 1.2.

These plots showed the relative effectiveness of the two alternative criteria which enabled recommendations to be made.

This report only considers the effect of horizontal irregularity on house torsional response. The effect of vertical irregularity on house torsional response was not considered.

Horizontal irregularity is defined as non-symmetry of bracing distribution in a plan view. Thus for two storey construction, the external walls of the upper storey align with the lower storey.

Vertical irregularity is defined as lack of symmetry over the height of the house. Two classic cases are illustrated in Figure 2:

(a) where upper floor(s) are set back from the lower floor or do not cover the full plan area

(b) where the house is stepped up a hillside with the back of each level fixed to the ground (e.g. on concrete floor, stiff retaining walls or short stub piles), but the front (usually suspended timber floor) is supported on walls which can deflect. This is an extremely eccentric load case and yet allowed by NZS 3604. There is a risk that the timber floor could dislodge perpendicular to the concrete floor and diaphragm separation may occur.

(a) Showing floor setback **(b) Showing building stepping**

Figure 2. Examples of vertical irregularity.

Section 2 describes the modelling assumptions of an “idealised” house. This includes the computer model, earthquake records, the selection of house wall properties, house mass and floor rotational inertia. The model was used to investigate the propensity of a house to twist due to horizontal irregularity.

Section 3 describes the results from torsional analysis of a symmetrical, “idealised”, single storey house. N-S and E-W earthquake loadings were separately analysed. For each direction a series of computer runs used different distances from the house centre-of-mass (C.O.M.) to the house geometric centre (C.O.B.). This is called the mass eccentricity. With zero eccentricity no twist occurs when the C.O.M. coincides with the centre of rigidity. These analyses are used as a reference to the behaviour of the modelled house when the distributions of wall strength/stiffness were varied.

Section 4 describes the results from torsional analysis of the “idealised”, single storey house using five wall strength distributions. The first distribution was the symmetrical house analysed in Section 3. The other distributions successively increased the number of walls which had a strength reduction to the minimum strength specified in NZS 3604 [1]. The N-S and E-W earthquake loadings were separately analysed. The house response is plotted against mass eccentricity.

Section 5 is the same as Section 4, but the minimum strength was made to comply with the writer’s criteria of Section 1.2 rather than the NZS 3604 criteria.

Section 6 provides a sensitivity analysis of the results to variations in assumed wall hysteresis loop properties, excitation earthquakes used and house shape (“L”-shaped rather than rectangular).

Section 7.1 compares the seismic response of a two storey “idealised” house to a single storey “idealised” house.

Section 7.2 compares the results of a two storey house with a single storey house for a realistic house, called the Alf house.

Section 8 compares the seismic response of a single storey Alf house with single storey “idealised” house.

Conclusions are given in Section 9.

The charts showing results are summarised in Table 1. The key to this table is given below:

Key to Table 1.

Heading in Table 1	Key word	Description of meaning of key word
House	idealised	Single storey rectangular house shown in Figure 3.
	2 storey	Two identical storeys of the “idealised” house.
	Alf	Single or two storey realistic house shown in Figure 31.
	“L”-shaped	Single storey “L”-shaped house shown in Figure 26.
EQ direction (Earthquake direction)	N-S	North-South direction i.e. parallel to the long sides of the page in house plan drawings in this report.
	E-W	East-West direction.
Bracing distribution	Uniform	All walls have been assigned a uniform strength per unit length as defined in Section 2.2.
	NZS 3604	The charts show results for five distributions of wall strength. In each distribution various walls, as defined in the text, have been given reduced strength/stiffness corresponding to the minimum allowable NZS 3604 bracing line strength as stipulated in Section 1.1.
	SJT1	The charts show results for five distributions of wall strength. In each distribution various walls, as defined in the text, have been given reduced strength/stiffness corresponding to the minimum allowable bracing line strength defined as the writer’s criteria in Section 1.2.
	SJT2	As per SJT1 but 1.5 x the minimum strength of the SJT1 bracing lines.
Section		Section number where chart is described.
Figure		Figure number assigned to chart.

Table 1. Summary of computer output plotted

No.	House	EQ direction	Bracing distribution	Section	Figure	Purpose To show:
1	Idealised	N-S	Uniform		11	Maximum movement of each corner
2	Idealised	N-S	Uniform		12	Influence of EQ factor on diaphragm rotation
3	Idealised	N-S	Uniform		13	Influence of EQ factor on maximum deflections
4	Idealised	N-S	Uniform		14	Influence of EQ factor on maximum deflections
5	Idealised	E-W	Uniform		15	Influence of EQ factor on diaphragm rotation
6	Idealised	E-W	Uniform		16	Influence of EQ factor on maximum deflections
7	Idealised	N-S	NZS 3604		18	Influence of wall stiffness distribution on maximum deflections
8	Idealised	N-S	NZS 3604		19	Influence of wall stiffness distribution on diaphragm rotation
9	Idealised	N-S	SJT1		20	Influence of wall stiffness distribution on maximum deflections
10	Idealised	N-S	SJT2		21	Influence of wall stiffness distribution on maximum deflections
11	Idealised	E-W	SJT1		22	Influence of wall stiffness distribution on maximum deflections
12	Idealised	E-W	SJT1		23	Influence of wall stiffness distribution on diaphragm rotation
13	Idealised	N-S	Uniform		24	Influence of K_0 factor on maximum deflections
14	Idealised	N-S	Uniform		25	Influence of EQ record on maximum deflections
15	"L"-shaped	N-S	NZS 3604		27	Influence of wall stiffness distribution on maximum deflections
16	"L"-shaped	N-S	NZS 3604		28	Influence of wall stiffness distribution on diaphragm rotation
17	Idealised/2 storey	N-S	Uniform		29	Comparing single and two storey response
16	Alf/2 storey	N-S	Uniform		30	Comparing single and two storey response
17	Idealised/Alf	N-S	Uniform		32	Comparing Alf and idealised house response

See previous page for key to this table.

2. COMPUTER MODELLING

2.1 Floor plan of “idealised” house

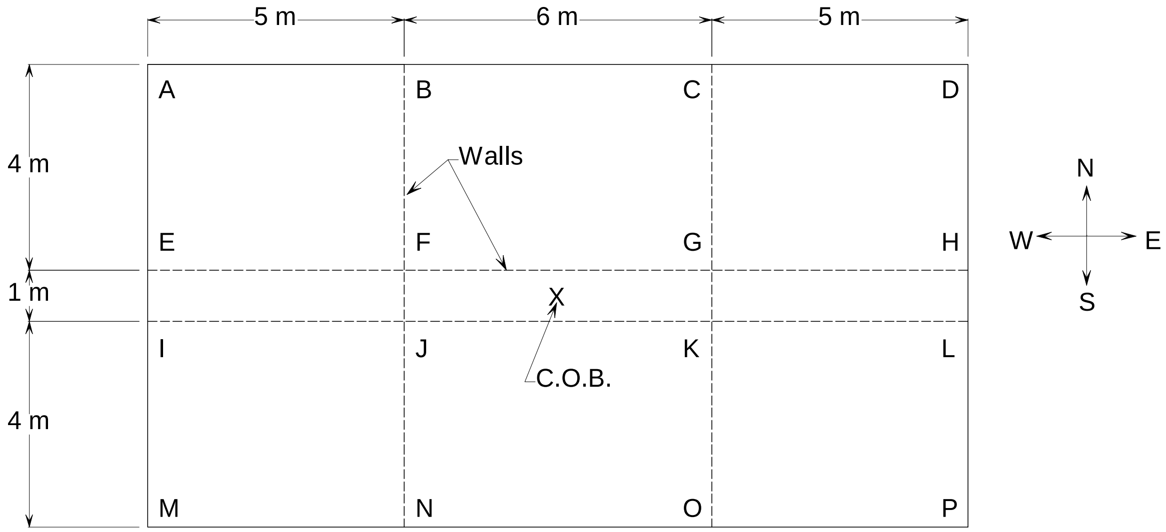


Figure 3. Single storey house plan
(External walls are shown with a full line and internal walls are shown dashed.)

The plan layout of walls is shown in Figure 3. Walls are aligned parallel with the main compass directions. An idealised layout of walls is used, but it is of value in that it is very simple and yet provides a reasonable distribution of bracing strengths. The house is symmetrical about the C.O.B. and would be considered to have little torsion susceptibility as the C.O.M. coincides with the centre of rigidity when the walls have a uniform stiffness per unit length. It was mostly analysed as a single storey house, although the two storey case was also examined. Sensitivity runs were also performed for different earthquake excitations and different element stiffnesses.

2.2 Wall strengths used in the computer analysis

2.2.1 Single storey idealised house using the symmetrical wall strength layout

It was assumed that the house demand horizontal earthquake load was 10 BU’s/m^2 = 0.5 kN/m^2. Thus, using the plan dimensions of Figure 3 the design lateral load = 0.5 x 16 x 9 = 72 kN. Earthquake demand loading specified in NZS 3604 for single storey houses on a concrete foundation vary between 1.8-11.2 BU/m^2. Demand values increase if there is a sub-floor. The strength of 10 BU’s/m^2 provided is considered to be reasonably representative.

(a) N-S direction

The house walls aligned in the N-S direction were assumed to have an average bracing strength, F_u, of 2 kN/m over their entire length which is the same as assuming the walls had an average bracing strength of 4.0 kN/m and 50% of the walls were gaps (i.e. windows or doorway openings). As the total length of walls in the N-S direction was 36 m, the house yield bracing strength was F_u = 36 x 2 = 72 kN or 18 kN for each of the four walls. Hence, a total wall strength of 72 kN was provided as required in the paragraph above.

(b) E-W direction

NZS 3604 allows interior walls within 2 m of each other to be considered as one bracing line. Thus, the two interior corridor walls in the E-W direction were considered to be one bracing line. This was assigned a combined strength of 24 kN. The external E-W walls were each also assumed to have F_u = 24 kN giving the total E-W wall strength of 3 x 24 = 72 kN (which is the same as the N-S direction).

2.2.2 Single storey idealised house with selected walls having reduced strength

Initially the building had the same strength/stiffness in both the N-S and E-W directions. Hence, it had the same building period in both directions. To examine the degree to which houses will twist under earthquake attack, computer runs were made where the strength/stiffness of selected walls were reduced to a minimum criteria. This reduced the total house strength/stiffness of the house. To ensure the building retained the same period for both directions the following procedure was used. (This is explained for loading in the N-S direction, but the same method was used for loading in the E-W direction.)

First, the strength of some N-S and perhaps also E-W walls was reduced from that specified in Section 2.2.1 to the minimum allowable by the torsion wall strength distribution criteria being considered. As reducing the strength of some N-S walls thereby reduced the total N-S strength of the house model, the mass was also reduced in the same proportion. Thus, if twist was suppressed, the house would deflect the same amount under a given earthquake. Further, the translation natural period of all the house would not change.

The total strength of the walls in the E-W direction was then set equal to the total strength of the walls in the N-S direction. This was achieved by setting:

$S_{Full} = TOTAL_{NS} – S_{Weakened}$ …………………… (1)

Where:

$TOTAL_{NS}$ = total strength of the all walls in the N-S direction.

S_{Full} = total strength of walls in the E-W direction whose strength has not been reduced by the torsion wall strength distribution criteria being considered.

$S_{Weakened}$ = total strength of walls in the E-W direction whose strength has been reduced by the torsion criteria.

S_{Full} was then divided equally between the bracing lines in the E-W direction whose strength had not been specifically reduced by the torsion criteria.

EXAMPLE

Consider the symmetrical house of Figure 4 labelled Distribution 1 under excitation by a N-S earthquake. The total strength in the N-S direction = F_u = 4 x 18 = 72 kN. Using the properties of the model summarised in Table 2, the house weight = 2.1 x F_u = 2.1 x 72 = 151.2 kN and the house stiffness = 180 x F_u = 180 x 72 = 12960 kN/m. The house period, T, is given by:

$$T = 2\pi\sqrt{\frac{W}{gK}} = 2\pi\sqrt{\frac{151.2}{9.81x12960}} = 0.217 \text{ seconds.}$$

If the NZS 3604 minimum criteria is now applied to the three walls shown with dashed lines in Distribution 4 of Figure 4, then the strength of these walls decrease to the values shown in Figure 4. The properties are now:

- the new N-S strength = 18 + 18 + 3.5 + 4.5 = 44 kN
- the new house weight = 2.1 x 44 = 92.4 kN
- the new house period, T, is given by:

$$T = 2\pi\sqrt{\frac{W}{gK}} = 2\pi\sqrt{\frac{92.4}{9.81x7920}} = 0.217$$ seconds – i.e. no change.

From eqn (1) S_{Full} = $TOTAL_{NS}$ – $S_{Weakened}$ = 44 – 8 = 36 kN

When this is divided equally between the two remaining bracing lines in the E-W direction (i.e. 18 kN to each of the two remaining walls) the final distribution is obtained as shown in Distribution 4 of Figure 4. Note that the period in the E-W direction is still 0.214 seconds.

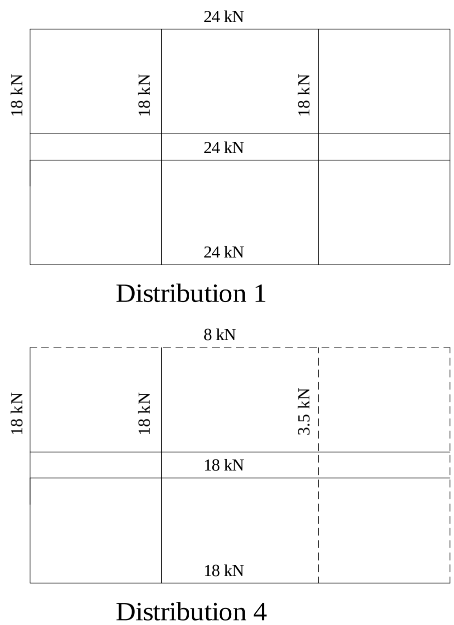


Figure 4. Example of stiffness changes for models with some walls assigned minimum strength of NZS 3604 criteria (N-S earthquake).

2.2.3 Two storey houses

The computer models were formed by using a second cruciform on top of the first (see Figure 9) with the same inter-storey stiffnesses and strengths being used between each level.

2.2.4 Alf house

A plan view of the Alf house is shown in Figure 31. The strength of the solid walls was assigned a bracing rating of 4 kN/m.

2.2.5 "L"-shaped house

The wall strength for the various stiffness distributions shown in Figure 26 used the same assumptions as for the idealised house.

2.3 Floor masses

2.3.1 Single storey model

The floor mass was selected to ensure the house had realistic deflections when excited by the design earthquake. In the BRANZ P21 test [2] the ultimate limit load cycling is normally performed in the 20-36 mm deflection band and in the EM3 test [4] the band is 20-30 mm. Plasterboard systems tend to be moderately brittle, and thus the target deflection for non-eccentric seismic loading in this study was taken as 24 mm. By a trial and error process, this was approximately achieved by setting the total house weight in kN, W= 2.1 F_u, where F_u is the sum of the wall strengths in the earthquake direction being considered (see Table 2). However, as this study was involved in the prediction of the relative increase in wall deflection due to torsion effects, the mass used in the model is of little consequence provided it leads to realistic deflections.

In some computer runs the racking strength of some walls was reduced, thereby reducing the total strength of the house. The masses were also reduced in proportion to the strength in the direction of loading. Thus, if house twist is suppressed all analysed houses deflected the same. Further, the translation natural period did not change. The house first mode period was constant for all houses analysed (0.217 seconds).

It is likely that most New Zealand houses will be stiffer than modelled due to the mass of houses being less than assumed in the NZS 3604 design method and stiffness being greater due to systems effects. Systems effects are discussed in detail by Thurston [12].

2.3.2 Two storey model

The same total house mass as for the single storey models was used, with 43% being distributed to the roof level and 53% to the first floor level and the same mass eccentricities being used at each level. At both levels, the same wall strengths and distributions were assumed as per the single storey model.

Thus, it was assumed that the house demand load for the lower storey was 10 BU's/m^2 = 0.5 kN/m^2, which is the same as was assumed for the single storey model. Hence, the design lateral load also remained at 72 kN. The range of bracing demand values from NZS 3604 is 5-24.3 BU's/m^2. As expected, the upper storey walls remain almost elastic while the bottom storey walls yielded in the analysis. Doubling the total mass and inter-storey stiffnesses will not affect the computed deflections.

2.4 Details of the single storey computer model

The inelastic time history computer analysis used the well known Ruaumoko [5] software.

A schematic depiction of the computer model is shown in Figure 5. It consisted of a 'cruciform' shape of very stiff members (representing a rigid floor/ceiling diaphragm) connected by springs to rigid supports. These springs represented walls spanning between the ground and the diaphragm. For example, spring ABCD in Figure 5 represents the wall ABCD shown on the plan of Figure 3.

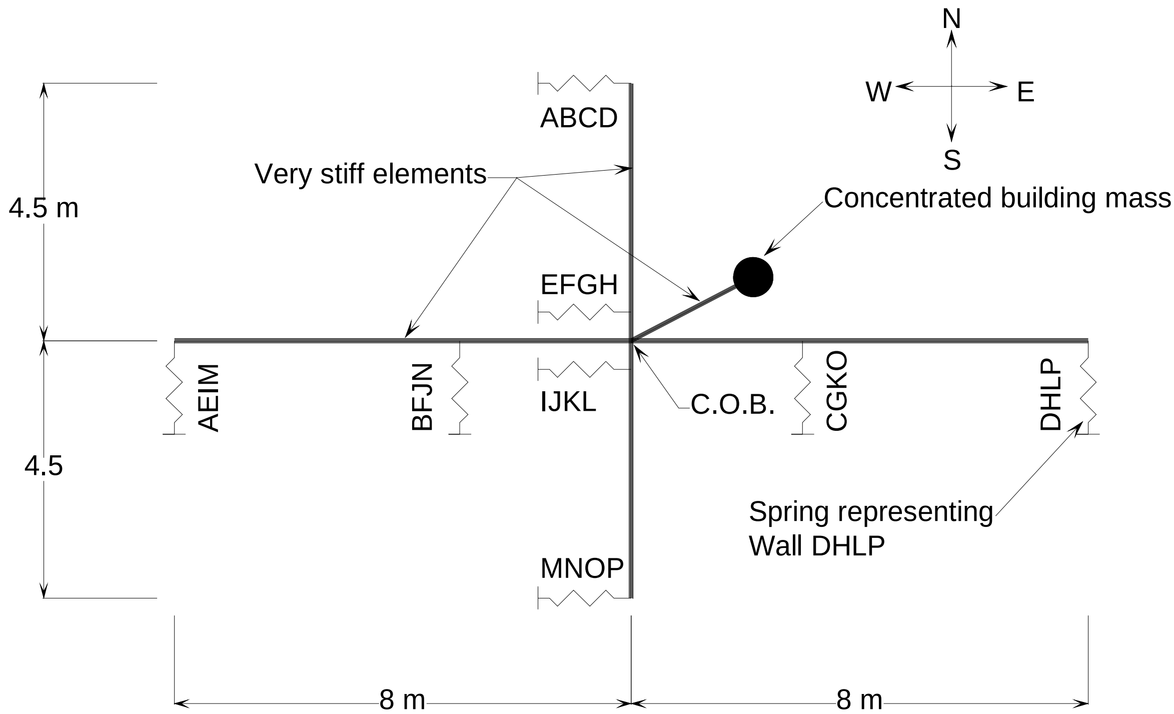


Figure 5. Computer model of house.

As already mentioned, C.O.B. is defined as the geometric centre of the building, which will coincide with the C.O.M. if the building has a uniform weight per unit area. If the walls have a uniform stiffness per unit length (i.e. Distribution 1) the C.O.B. also coincides with the centre of rigidity for the idealised building of Figure 3.

The floor mass was connected to the C.O.B. by a very stiff member and its location was varied between runs to investigate the relationship between house twist and distance between house C.O.M. and the C.O.B. The mass was assigned a rotational inertia, $I_{r,}$ which was calculated assuming the mass is uniformly distributed over the plan floor area. Thurston [12] calculated this rotational inertia as:

$I_r = M(D^2 + B^2)/12$ where M = floor mass, and D and B are the plan dimensions of the floor.

The springs were modelled using the Stewart [7] hysteresis element shown in Figure 6. Parameters used are shown in Table 2. Values of F_u used are defined for each particular computer run in the text. The value of K_0 used was based on examination of BRANZ P21 tests of various plasterboard wall systems.

Table 2. Stewart hysteresis element spring properties

Spring property	Value assigned
Ultimate spring axial strength representing wall shear strength	F_u
Spring initial stiffness K_0 (kN/m)	180 x F_u
Secondary slope	$0.21K_0$
Tertiary slope	Zero
Unloading slope K_u	1.3 K_0
Yield F_y	$0.58F_u$
Intercept, F_I	$F_u/6$
ALPHA	1.09
BETA	0.38

The shape of the hysteresis loops defined by Table 2 are plotted in Figure 7 and are compared with test results for a 1.2 m long wall lined on both sides with standard 10 mm thick plasterboard.

The line joining the first cycle peak loads is herein called the 'parent' curve and the line joining the second and subsequent cycle peak loads is called the 'residual' curve. The 'parent' curve for the model hysteresis element shown in Figure 7 reached peak load at 14 mm deflection and retained this load at higher deflections, and in this respect slightly departed from the test specimen shown. On the other hand the 'residual' curve closely followed the test specimen plot.

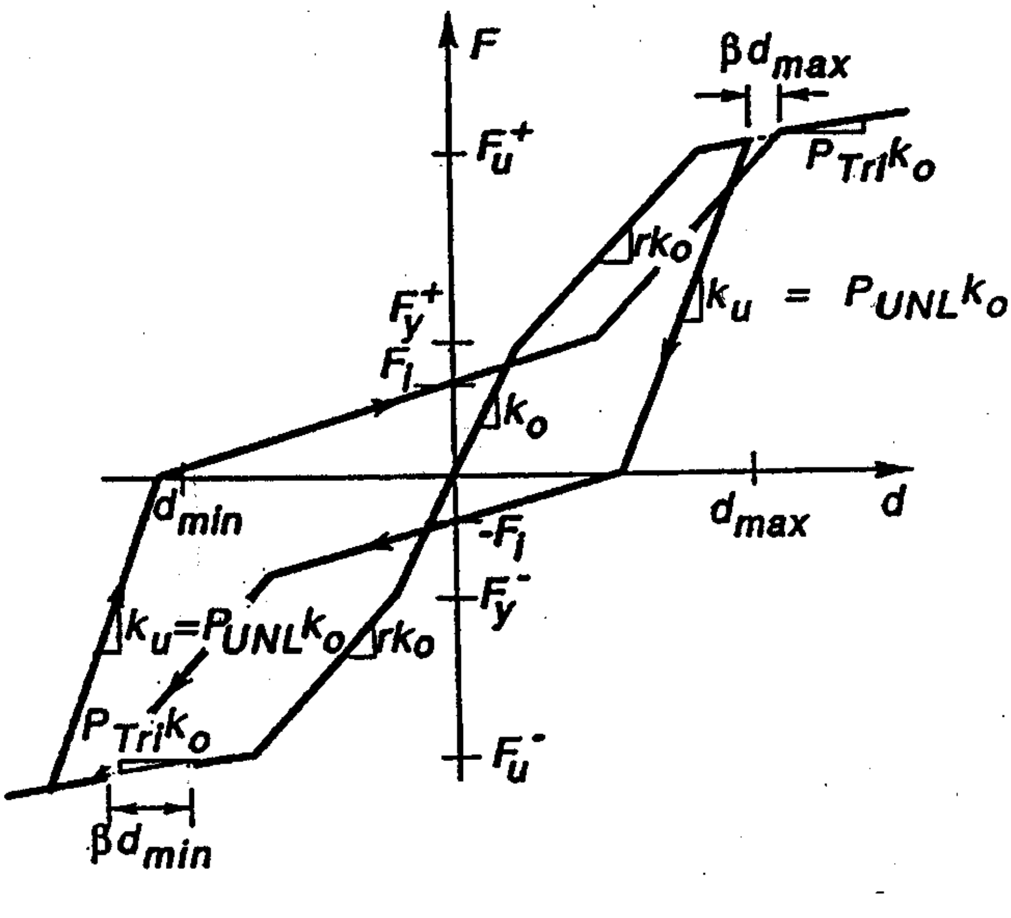


Figure 6. Terminology for Stewart hysteresis element.

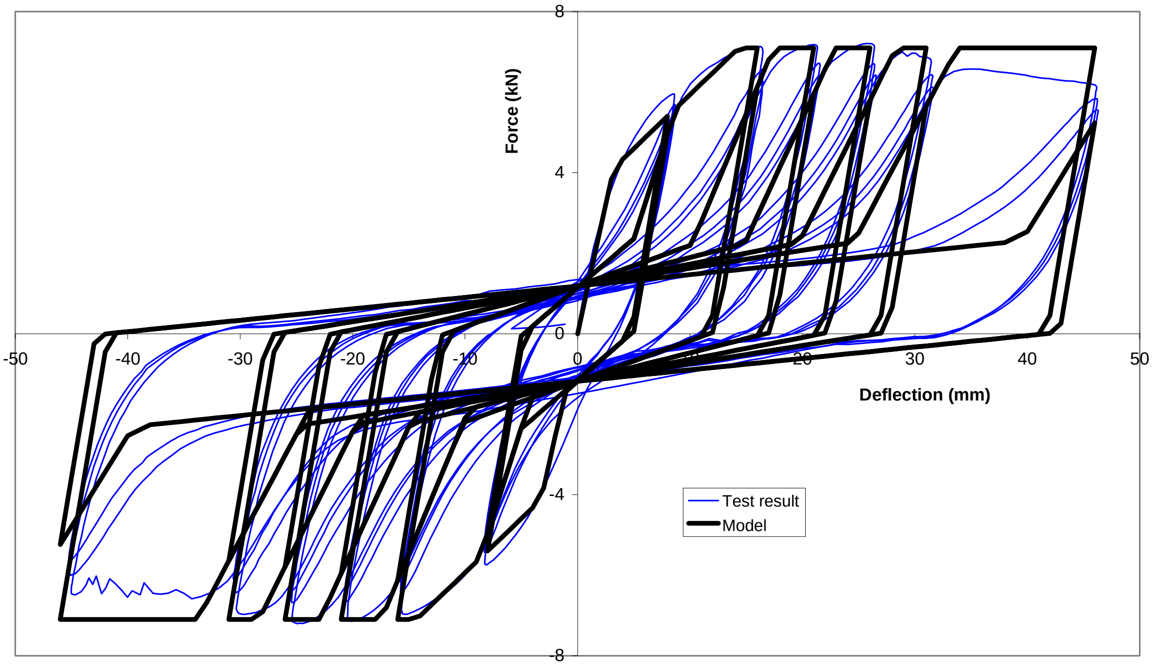


Figure 7. Comparison of Stewart hysteresis model and test data.

2.5 Details of the two storey computer model

The two storey computer model was the same as the single storey computer model except as described in the paragraph below.

The two storey computer model was formed by using a second cruciform on top of the first (see Figure 9) with the same inter-storey stiffnesses/strengths and distributions being used between each level. The same total house mass was used with 43% being distributed to the roof level and 53% to the first floor level and the same mass eccentricities being used at each level.

2.6 Earthquake records

This study used a modified El Centro earthquake provided by Davidson [8]. This had elastic spectra corresponding to the design elastic spectra of Figure 4.6.1(b) in NZS 4203:1992 [9]. Other artificial earthquakes which fitted the spectra were used in sensitivity analyses. These records provide a good fit to the NZS 4203 design spectra. Although it is recognised that this suite of earthquakes may be somewhat conservative because the records had excessive energy, the developer of the earthquake records commented [11]:

- the method used to develop the records was standard
- the New Zealand standard [10] did not provide limits on earthquake energy
- the conservatism would be small.

Further, because this study only investigates the relative deflection due to house twist, any conservatism of earthquake record is of little significance.

2.7 Computer modelling of the floor diaphragm

2.7.1 Diaphragm model

The diaphragm was modelled with very stiff beam elements as shown in Figure 5. The shear walls were modelled as springs representing walls spanning between ground and the diaphragm with properties discussed in Section 2.2. The flexural and shear stiffness of diaphragms can be modelled by adjusting the properties of the beam elements, but this was not considered necessary in this project as the diaphragm stiffnesses are relatively high compared to wall stiffnesses. (Note that the slip between adjacent plasterboard sheets is unlikely as these joints are taped and stopped.) Relative movement at the connection between the diaphragm and shear wall is expected to be significantly less than wall racking deflection. It can be included in the model (for each spring) by adding the shear wall and connection flexibilities. However as connections are likely to slip only a few millimetres, whereas shear wall deflections may be an order of magnitude greater, and as the shear wall hysteresis loops were only representative of estimated average behaviour, connection flexibility was not specifically included in the analysis.

2.7.2 Calculation of maximum shear wall deflection

If the deflection at, and rotation of, a specific point on a rigid diaphragm is known, then the deflection of every other point on the diaphragm can be calculated (see Figure 8). In this study, the geometric house centroid, shown as C.O.B. in Figure 3, was used as this specific point. If this point has coordinates of ($X_{C.O.B.}$, $Y_{C.O.B.}$) and experiences deflections ($\Delta_{XC.O.B.}$ and $\Delta_{YC.O.B.}$) and rotation (θ) then the deflection of an arbitrary point $P_{(X,Y)}$ on the diaphragm is given by:

$\Delta_X = \Delta_{XC.O.B.} + \theta\,(Y - Y_{C.O.B.})$ and $\Delta_Y = \Delta_{YC.O.B.} + \theta\,(X - X_{C.O.B.})$ …… (1)

A corollary of this is that the walls along any bracing line will all have the same in-plane deflection. The ability of walls to sustain out-of-plane deflections was not considered in this project, but is not expected to be critical.

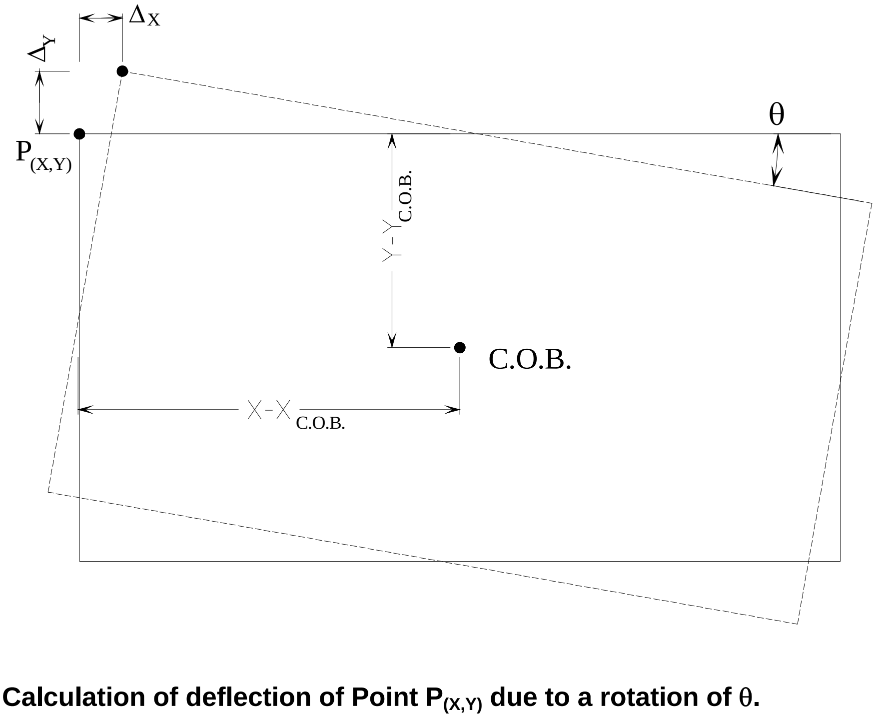


Figure 8. Calculation of deflection of Point $P_{(X,Y)}$ due to a rotation of θ.

2.8 Batch processing of analyses and results

Computer runs were performed for different mass eccentricities and for different earthquake excitation levels.

The analysis procedure used batch processing as follows. Each chart plotted required a large number (between 100 and 200 – say "N") Ruaumoko analyses. An MS Office Excel spreadsheet created the "N" Ruaumoko input files and a batch file. Clicking the batch file in MS Office Explorer ran the "N" Ruaumoko analyses, generating "N" output files. These were interrogated using a specially written Visual basic program which summarised the maximum deflections of all nodes in the "N" runs in a single output file. This was copied back into the original Excel spreadsheet which provided the plots presented in this report.

2.9 Interpretation of results

Consider the symmetrical idealised house subjected to a N-S earthquake. For ease of reference to salient locations on the cruciform of Figure 5, points are referred to using compass notation as shown in Figure 9. Thus, Point 'N' is the north-most point.

Consider a chart where the response of a house is plotted against mass eccentricity for five different earthquake excitation levels. For each earthquake excitation level, 21 computer simulation runs were performed, with the location of the C.O.M. along the E-W axis being changed for each run. When the mass is eccentric from C.O.B. the cruciform will rotate, but due to the symmetry of the structure, Point 'O' will move along the N-S axis as shown in Figure 10. This figure illustrates the displacement of the diaphragm for a northwards movement of Point 'O' of a distance 'Y' and rotation of the diaphragm of 'θ'. The movements of the points are summarised in Table 3 and are useful in understanding the plots subsequently produced in this report. Plots are only given for the in-plane wall deflections, which are the E-W movements of Points 'N' and 'S' and the N-S movements of Points 'W' and 'E'. These E-W movements of Points 'N' and 'S' are the in-plane deflection of all walls lying along the line ABCD or MNOP respectively of Figure 3. Similarly the N-S movement of Points 'W' and 'E' are the in-plane deflection of all walls lying along the line AEIM or DHLP respectively of Figure 3. Thus, the maximums movements found from these plots are the maximum in-plane deflections of walls within the entire structure.

Irrespective of the magnitude of Y in Figure 10, Table 3 shows that the maximum in-plane movement of the house walls in a N-S earthquake can be found from the movement of Points 'E' and 'W'. This is because the magnitude of the diaphragm twist induced N-S movement at Points 'E' and 'W' (i.e. 8000 x θ) is always greater than the magnitude of the diaphragm twist induced movement at Points 'N' and 'S' (i.e. 4500 x θ). For an E-W direction earthquake, the movement at all four points needs to be considered.

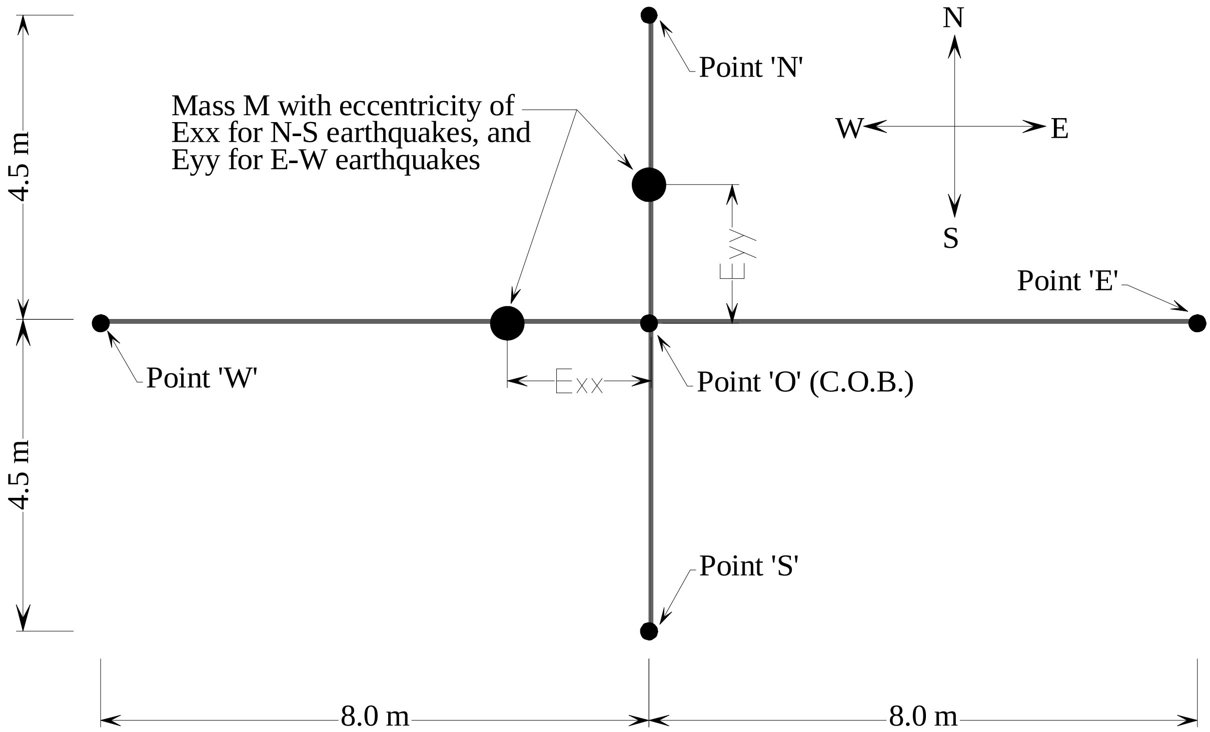


Figure 9. Notation used to reference to salient points on the cruciform.

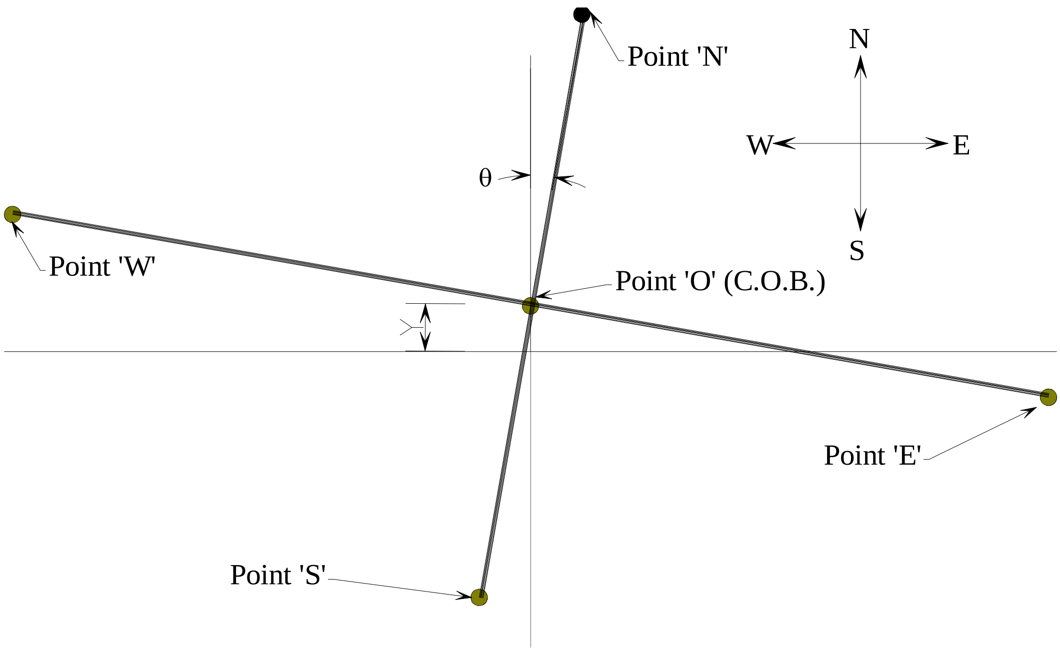


Figure 10. Movement of points under N-S earthquake.

Table 3. Movement of salient points in a N-S earthquake.

Location	Northwards displacement (mm)	Eastwards displacement (mm)
Point 'O'	Y	0
Point 'N'	Y	4500 x θ
Point 'S'	Y	-4500 x θ
Point 'E'	Y + 8000 x θ	0
Point 'W'	Y - 8000 x θ	0

3. ANALYSIS OF IDEALISED SYMMETRICAL SINGLE STOREY HOUSE

3.1 N-S earthquake

The house wall strengths are given in Section 2.2.1. As they are completely symmetrical about both axis no twist will occur when the C.O.M. coincides with the floor geometric centre (Point C.O.B. in Figure 3.)

Figure 11 is a plot of the maximum in-plane deflection of walls in a N-S earthquake plotted against the eccentricity of the C.O.M. from the C.O.B. The south movements of a particular point are close to (but not precisely) a mirror image about the horizontal axis of the north movements but occur at different earthquake excitation times. Similarly the north movements of a Point 'E' are close to (but not precisely) a mirror image of the north movements of Point 'W' about the vertical axis.
For zero eccentricity the maximum deflection = 23.8 mm which is close to the target deflection for this exercise (see Section 2.3).

Figure 12 plots the floor diaphragm rotation for both the standard earthquake excitation and for the excitation factored by 1.25, 0.75 and 0.5. At zero eccentricity the rotation is zero. All rotations plotted are less than $3x10^{-3}$ radians. Using the formula in Table 3, a rotation of $3x10^{-3}$ radians will move point 'W' in the north direction by $3x10^{-3}$ x 8000 = 24 mm (and point 'E' in the south direction by 24 mm). This indicates that deflection due to rotation is of a similar magnitude to the deflection from direct translation.

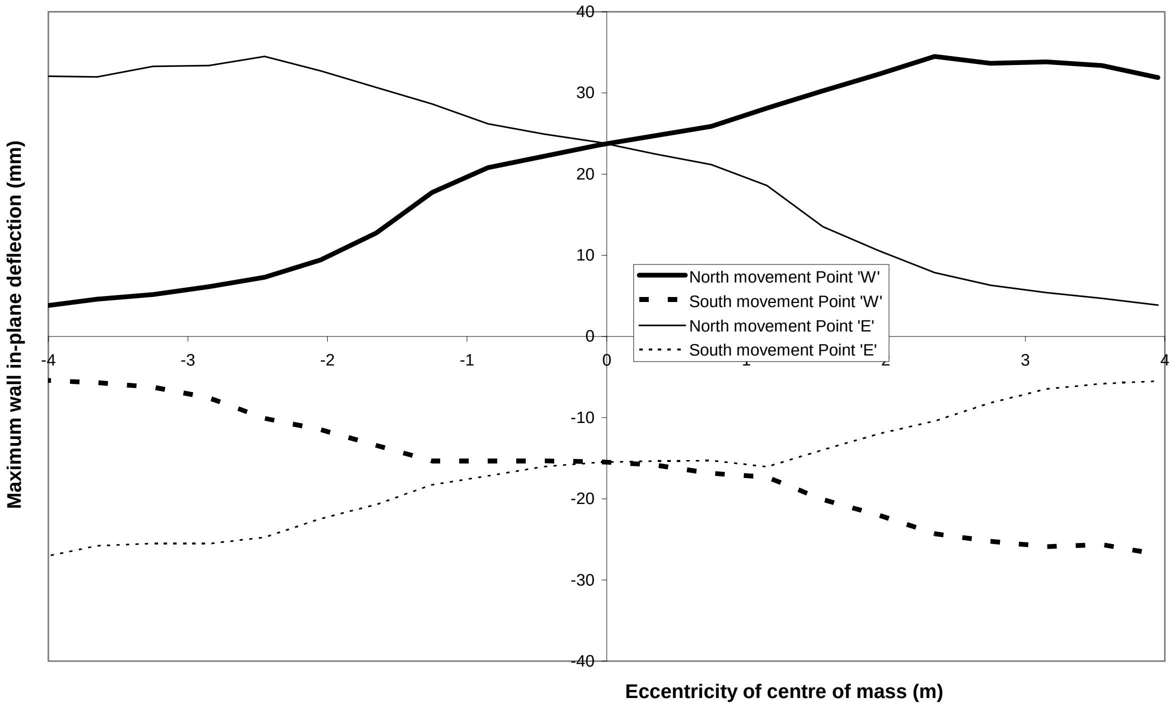


Figure 11. Maximum movement of Points ‘W’ and ‘E’.

- *The model is the single storey idealised house*
- *N-S earthquake excitation*

The maximum <u>magnitude</u> of the in-plane movement is plotted in Figure 13 for both the standard earthquake excitation and for the excitation factored by 1.25, 0.75 and 0.5. This shows that house deflection increases more than in proportion to increases in earthquake excitation ratio due to the non-linear spring stiffness used.

Figure 14 replots the same data to show the increase in deflection at 0.1B and 0.2B mass eccentricity. It can be seen that mass eccentricity does not have a large effect on total house deflection for this well conditioned house. At large earthquake factors a doubling of eccentricity causes little increase in deflection – probably because the effective house period is increasing as bracing elements degrade.

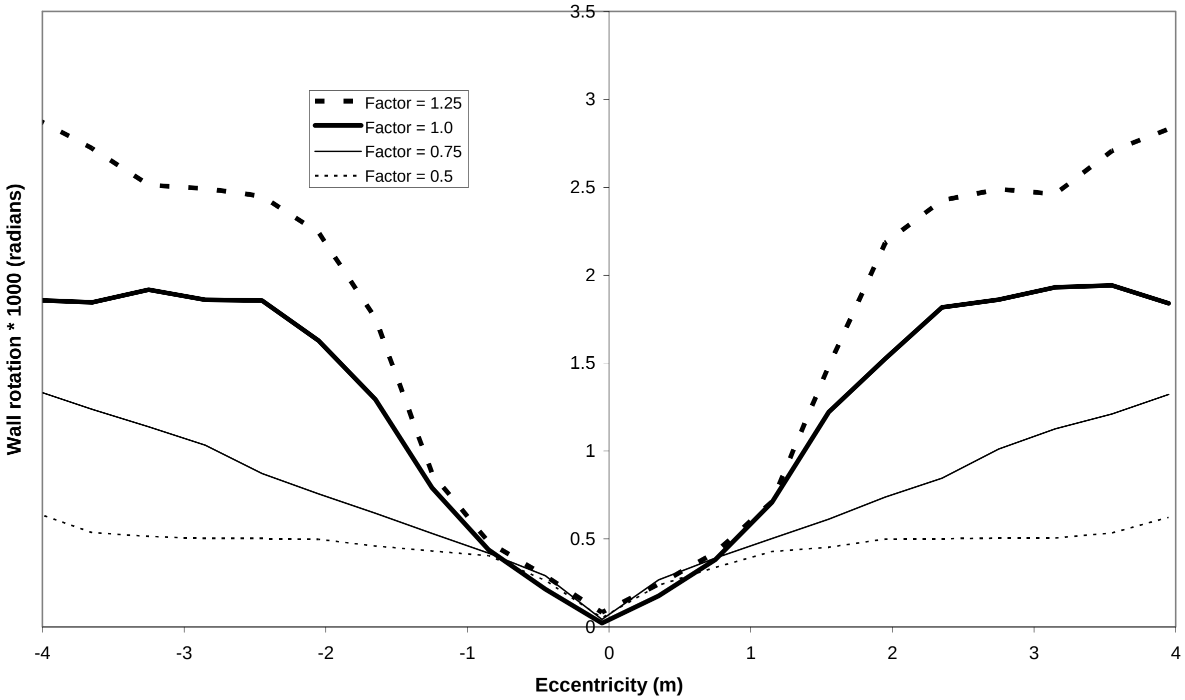


Figure 12. Maximum diaphragm rotation versus mass eccentricity.

- *Plots are given for four different earthquake excitation factors*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

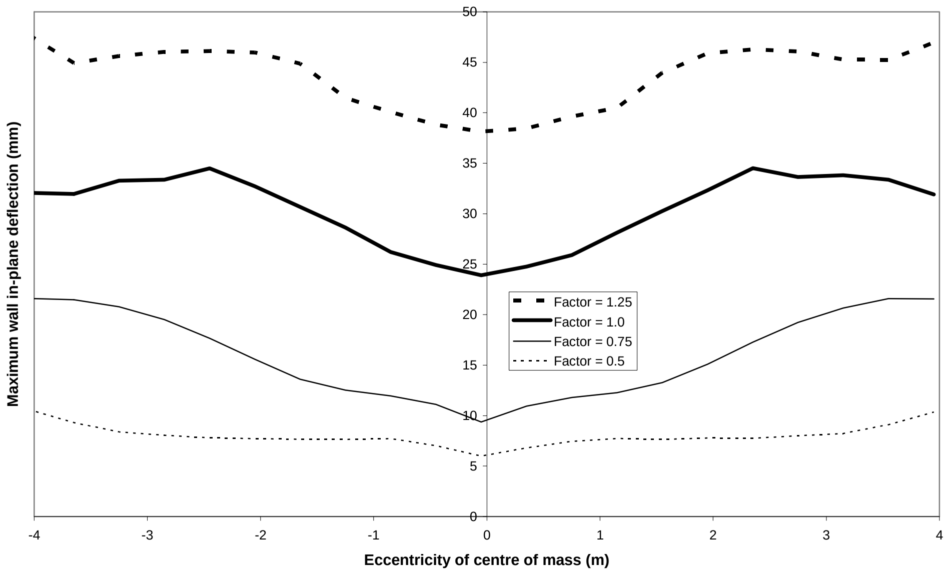


Figure 13. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for four different earthquake excitation factors*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

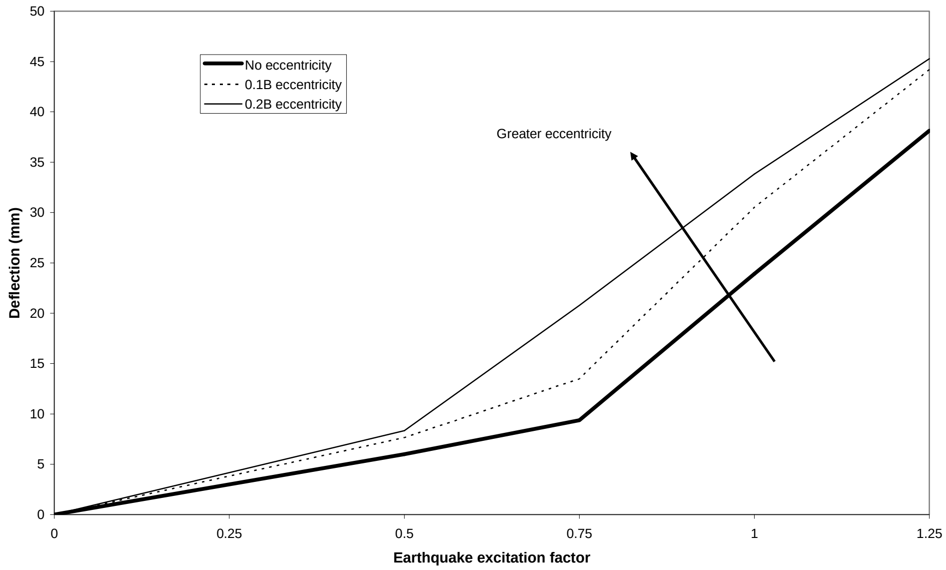


Figure 14. Maximum wall in-plane deflection versus earthquake excitation factors for various mass eccentricity.

- *The model is the single storey idealised house*
- *N-S earthquake excitation*

3.2 E-W earthquake

The wall layout is the same as for the N-S earthquake.

The amount of house twist for earthquakes in the E-W direction (Figure 15) is similar to that for earthquakes in the N-S direction (Figure 12), which is not surprising as the same walls are resisting this twist. However, because the walls in the E-W direction are at a smaller distance from the C.O.B. the house twist is expected to have a smaller influence on the deflection of walls which are parallel to the earthquake motion. This expectation is borne out by the analysis as can be seen from comparison of Figure 13 and Figure 16.

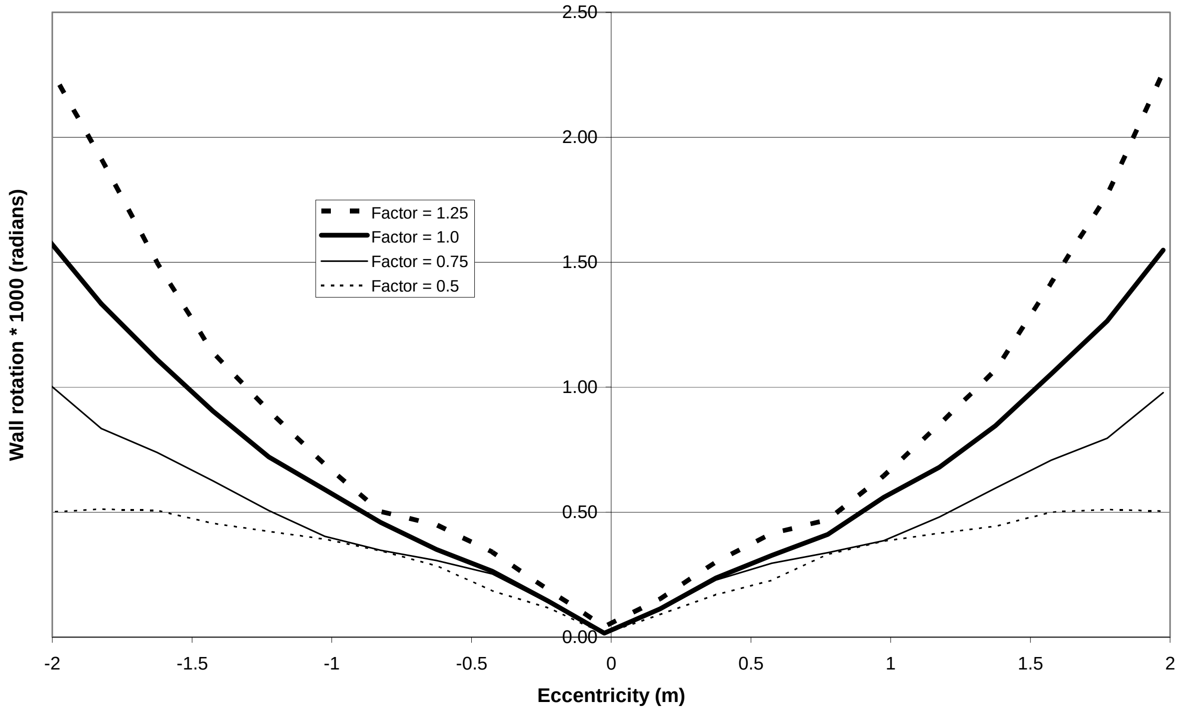


Figure 15. Maximum diaphragm rotation versus mass eccentricity.

- *Plots are given for four different earthquake excitation factors*
- *The model is the single storey idealised house*
- *E-W earthquake excitation*

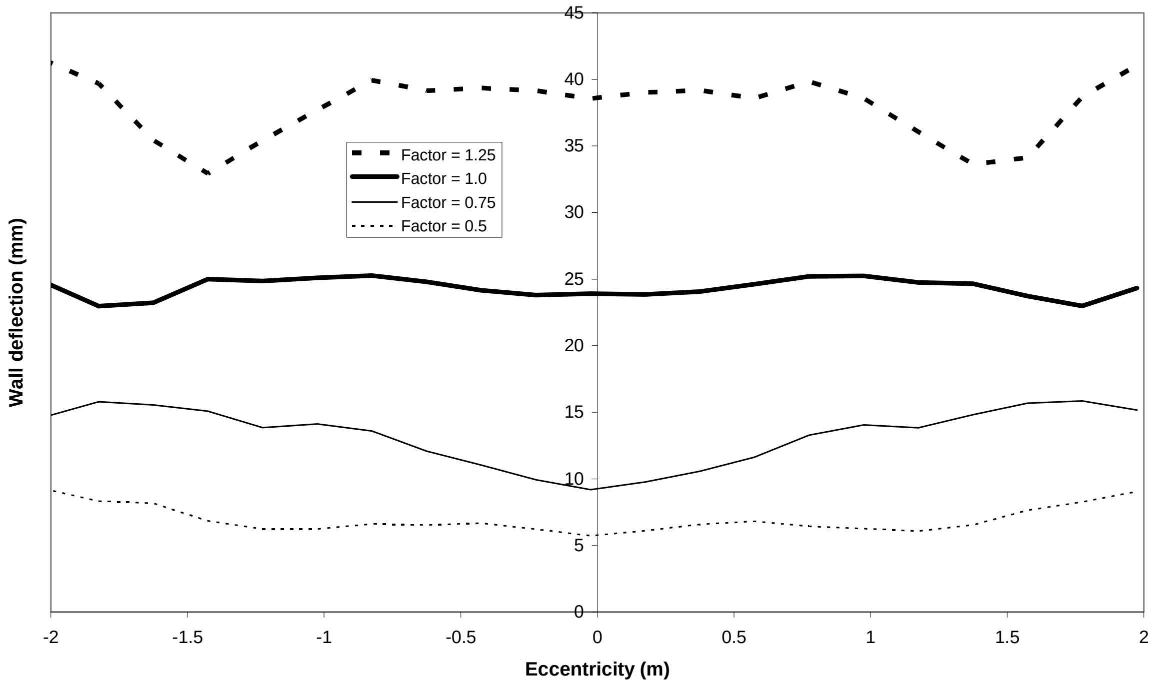


Figure 16. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for four different earthquake excitation factors*
- *The model is the single storey idealised house*
- *E-W earthquake excitation*

4. ANALYSIS OF IDEALISED SINGLE STOREY HOUSE WITH STIFFNESS DISTRIBUTIONS COMPLYING WITH NZS 3604

4.1 N-S earthquake

Five wall strength distributions were used as shown in Figure 17. The first was the symmetrical house analysed in Section 3. The other distributions successively increased the number of walls which had a strength reduction to the minimum strength which still complied with NZS 3604 [1]. This is a strength of 0.5 kN/m for external bracing walls and 3.5 kN for internal bracing lines. These walls are depicted with dashed lines in Figure 17. These wall stiffnesses were also reduced in proportion to the strength as detailed in Table 2.

As reducing the strength of some walls thereby reduced the total strength of the house model, the masses were also reduced in proportion to the strength in the direction of loading. Thus, if house twist is suppressed then all models have the same maximum deflection (23.8 mm – see Section 3.1). Further, the translation natural period of all models did not change.

Figure 18 plots the maximum wall deflections in the house versus mass eccentricity and Figure 19 plots the corresponding house rotations. Rotations are zero for Distributions 2 to 5 at the high negative eccentricities where the C.O.M. aligns with the centre of stiffness. It will be noted that the house deflections in Figure 18 are relatively low at eccentricities corresponding to zero rotation in Figure 19.

The maximum deflections for Distributions 3-5 are excessive, being greater than 42 mm at zero eccentricity and greater than 64 mm at an eccentricity of 1.6 m (0.1B) where B is the house width.

4.2 E-W earthquake

For reasons discussed in Section 3.2, the maximum wall deflections are not greatly increased by torsion effects (Figure 20), although the house rotation (Figure 21) is similar to that for earthquakes in the N-S direction (see Figure 19).

5. ANALYSIS OF IDEALISED SINGLE STOREY HOUSE WITH STIFFNESS DISTRIBUTIONS COMPLYING WITH THE WRITER'S DISTIBUTION

5.1 N-S earthquake – writer's distribution (SJT1)

The houses analysed were similar to those in Section 4.1, but the minimum strength used was from the criteria outlined in Section 1.2. i. e. the strength of the walls shown with a dashed line in Figure 17 was the minimum specified in Section 1.2.

The results are shown in Figure 22. If the SJT1 criteria is successful in reducing torsional effects, there will be little difference between the deflections determined using Distribution 1 with those determined using Distributions 2-5 – at least up to mass eccentricities of ±0.1B (1.6 m). It can be seen that this has been achieved to a moderate extent and the writer proposes that this criteria now be adopted.

5.2 N-S earthquake – 1.5 x writer's distribution (SJT2)

The houses analysed were similar to those in Section 5.1, except the minimum strength was the 1.5 x the criteria outlined in Section 1.2. i.e. the minimum strength of the walls shown with a dashed line in Figure 17 was 1.5 x the minimum specified in Section 4.1.

The results in Figure 23 show very little increase in house deflection with the Distributions 2-5 from Distribution 1. The writer suggests that distribution SJT2 is too conservative.

6. SENSITIVITY ANALYSIS

6.1 Sensitivity of results to variation of hysteresis loop initial slope

The sensitivity of results to the initial slope stiffness of the hysteresis loops K_0 (defined in Figure 6) is shown in Figure 24. Note that K_0 also changes the unload slope $K_u = P_{UNL}K_0$. However, the secondary (rK_0) and tertiary slope ($P_{Tri}K_0$) was left unchanged.

Changing wall stiffnesses has a large effect on the house response, which is expected as these changes the house natural period. The stiffer the house the less the deflection. The high sensitivity of the computed deflections was not considered to be a concern as all models (apart from in the sensitivity analysis) used the same hysteresis spring elements and the mass were set to give the same natural period. Therefore the changes in deflection due to twist between different wall stiffness distributions is comparable.

6.2 Sensitivity of results to variation of earthquake record

All earthquakes used were normalised to the NZS 4203 [10] design spectra. Figure 25 shows that the computed maximum deflections are not sensitive to the earthquake selected.

6.3 Sensitivity of results to variation of house shape

The analysis above was on a rectangular “idealised” house shown in Figure 3. Similar results would be expected for houses with different shapes as the basic model shown in Figure 5 remains the same, and removing a portion of a rectangular house to make say an “L”-shaped house removes both house mass and resisting walls. This was verified by analysing an “L”-shaped house for the stiffness distributions shown in Figure 26. The assumptions were the same as that used when analysing the “idealised” house.

A comparison of the maximum deflections for the “idealised” and “L”-shaped houses in Figure 18 and Figure 27, and a comparison of the maximum diaphragm rotations in Figure 19 and Figure 28, shows that the “L”-shaped house twist under earthquake attack was similar to that for the “idealised” house. It is thus concluded that the “idealised” house was a suitable model for this study.

7. COMPARISON OF SINGLE AND TWO STOREY HOUSE TORSIONAL RESPONSE

7.1 Idealised house

This was run to investigate whether a two storey house is more sensitive to torsion than a single storey house. The computer model was formed by using a second cruciform on top of the first (see Figure 5), with the same inter-storey stiffnesses and strengths being used between each level. The same total house mass was used with 43% being distributed to the roof level and 53% to the first floor level and the same mass eccentricities being used at each level. The plot of ground to first floor inter-storey deflections in Figure 29 is compared with the single storey equivalent. This indicates that the results for the two storey house were similar, but lower, than for the single storey house.

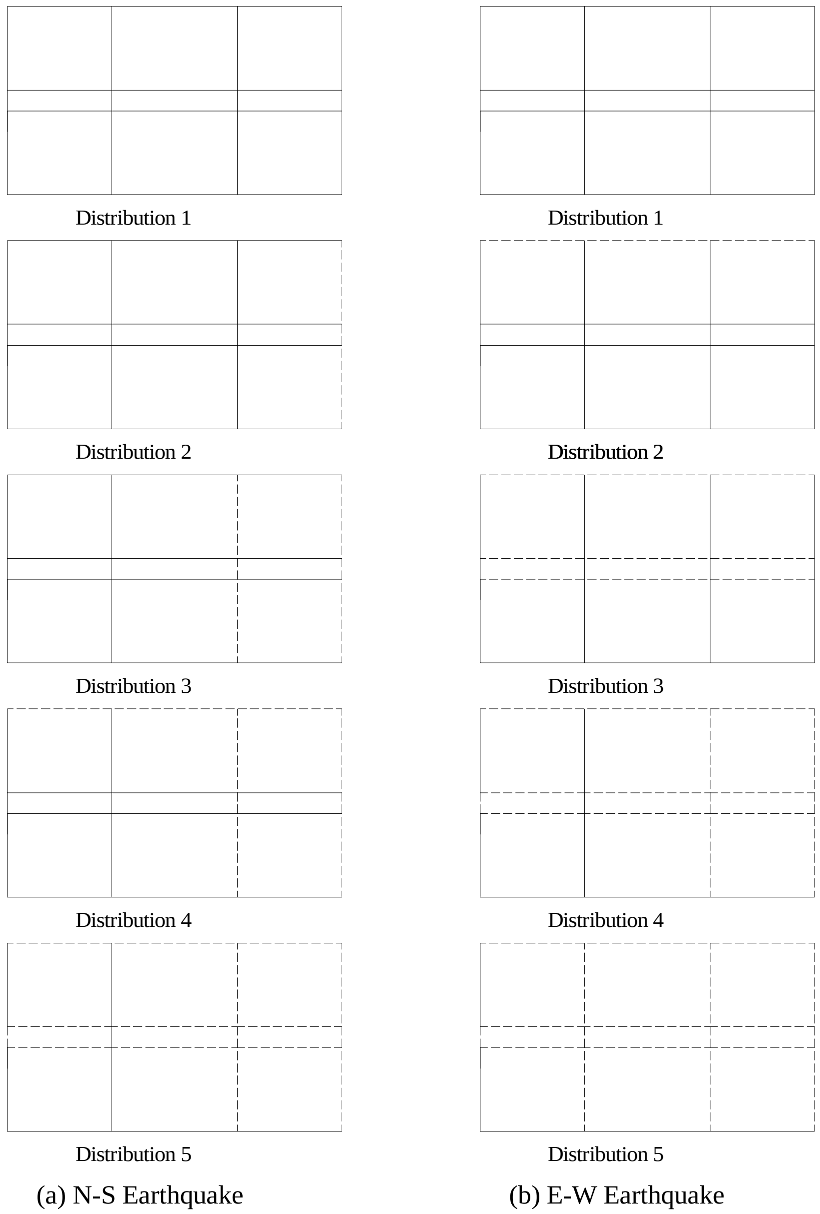
This result is expected as it is the same total mass driving the lower storey inter-storey deflections in both the single storey and two storey models but the top storey can become out-of-phase with the bottom storey which will reduce the lower storey deflections. As expected, runs where the total mass and inter-storey stiffnesses were doubled did not affect the result.

7.2 Alf house

The Alf one storey and two storey houses are intended to represent typical New Zealand houses and have realistic wall layouts (see Figure 31). These are defined in the BRANZ Alf manual [14]. These two houses were also analysed to investigate the difference in torsional response between a single and two storey house. The results in Figure 30 also indicate that torsion effects for two storey houses are similar, but slightly less severe, than for the single storey house. As correspondence of large mass eccentricities of both first floor and roof level masses is unlikely, it is concluded that torsion effects in two storey houses, due to plan irregularity, will generally be less severe than for single storey houses.

8. COMPARISON OF IDEALISED AND ALF HOUSE TORSIONAL RESPONSE

Figure 32 compares the maximum deflections computed for the single storey idealised house and the single storey Alf house for loading in the N-S direction. The Alf house was not symmetric and when analysed gave greater deflections for positive eccentricities than for negative eccentricities. However, overall the idealised and Alf house showed similar sensitivity to torsional loadings. This indicated that the idealised house was a reasonable model to use for this study.



The dashed lines represent the walls which are assigned the reduced strengths given in Section 1.1 for the NZS 3604 criteria and Section 1.2 for the writer's criteria.

Figure 17. Distribution of wall stiffnesses for computer runs using minimum wall strength based on torsional criteria.

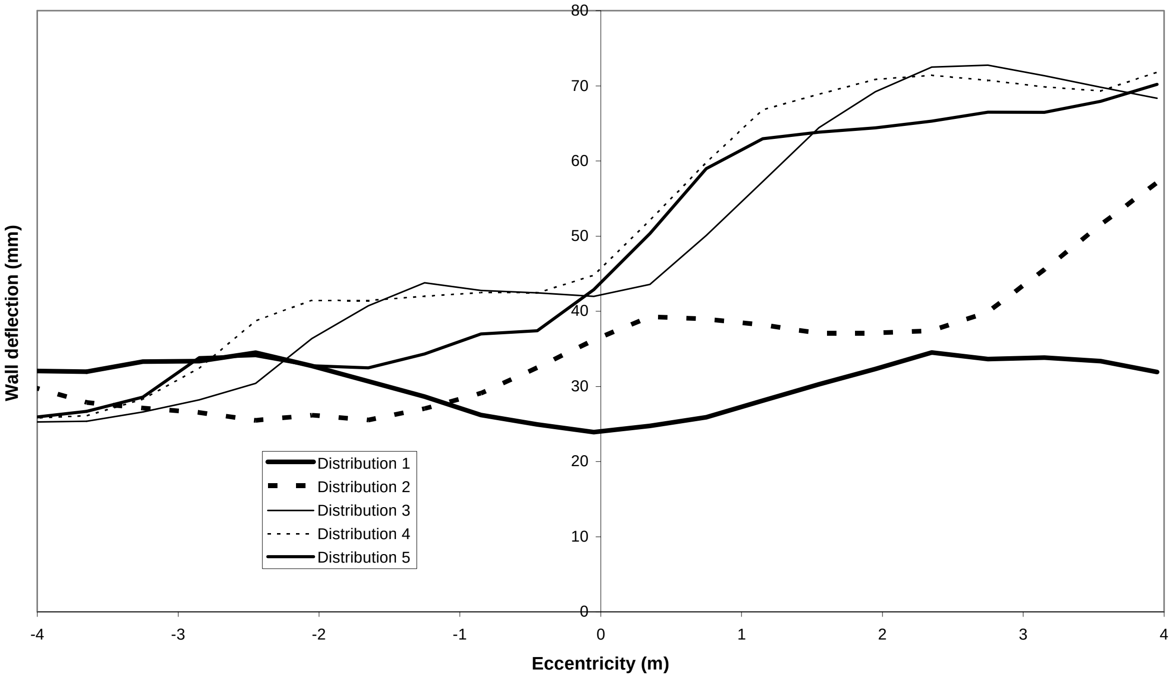


Figure 18. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for five NZS 3604 minimum bracing criteria wall resistance distributions*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

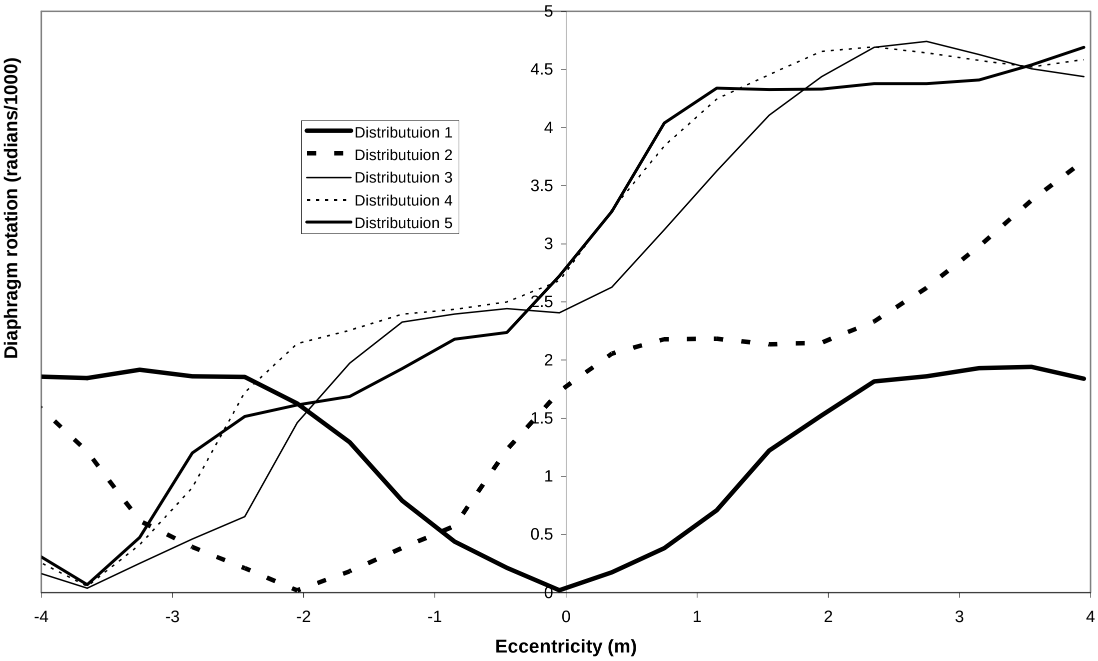


Figure 19. House rotation for different mass eccentricity.

- *Plots are given for five NZS 3604 minimum bracing criteria wall resistance distributions*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

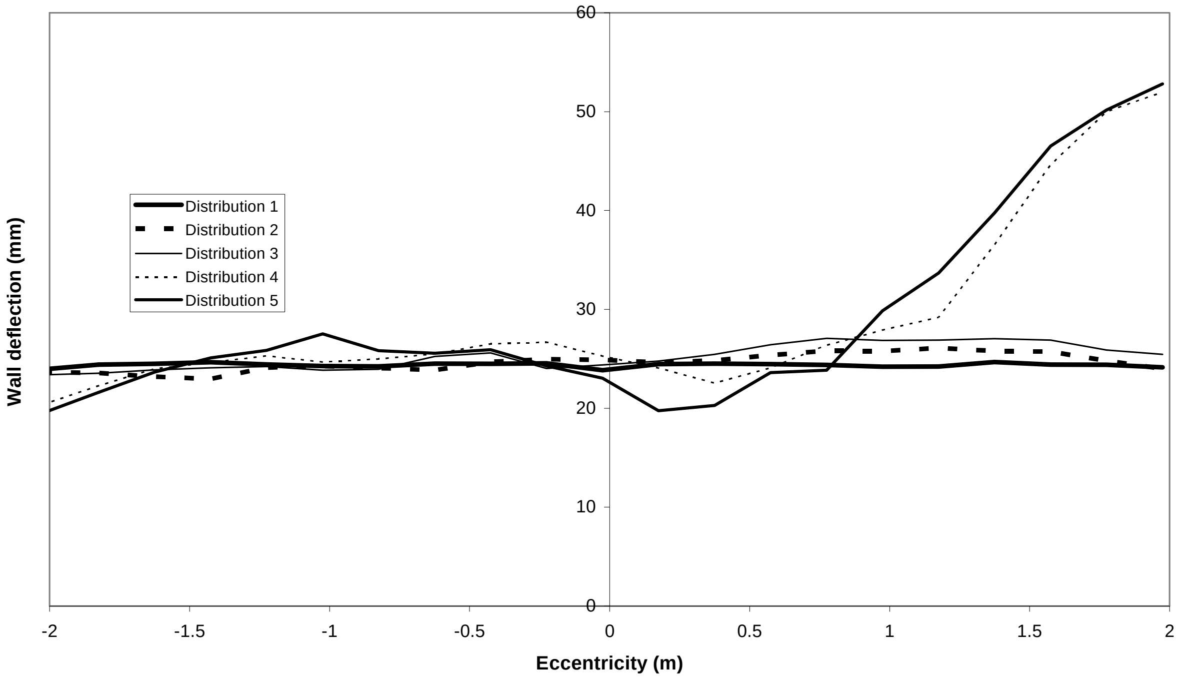


Figure 20. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for five NZS 3604 minimum bracing criteria wall resistance distributions*
- *The model is the single storey idealised house*
- *E-W earthquake excitation*

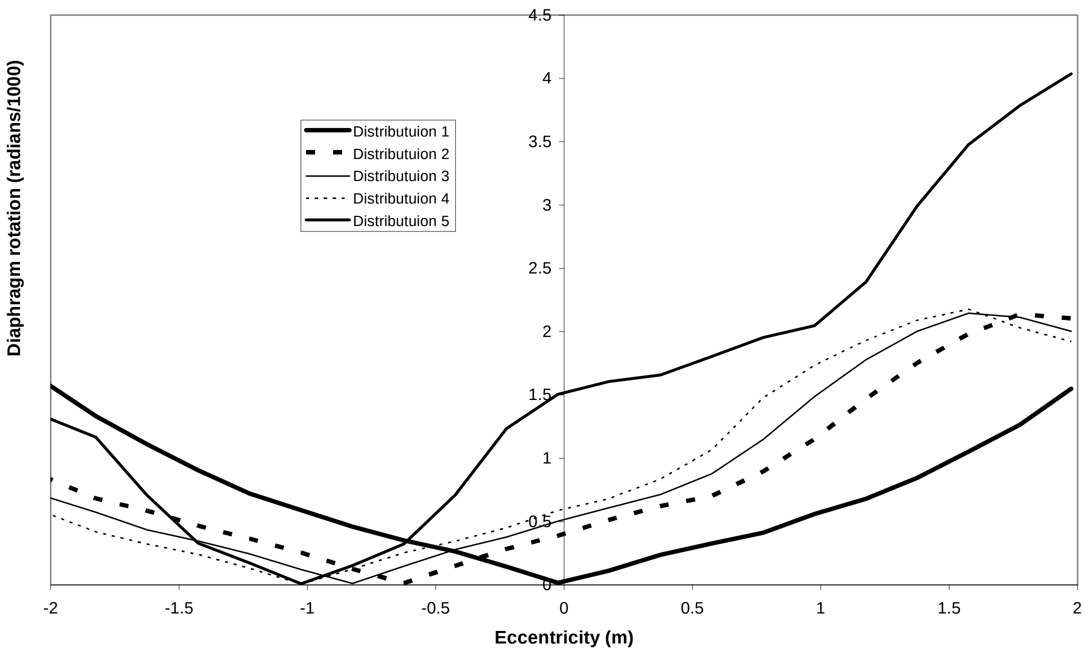


Figure 21. House rotation versus mass eccentricity.

- *Plots are given for five NZS 3604 minimum bracing criteria wall resistance distributions*
- *The model is the single storey idealised house*
- *E-W earthquake excitation*

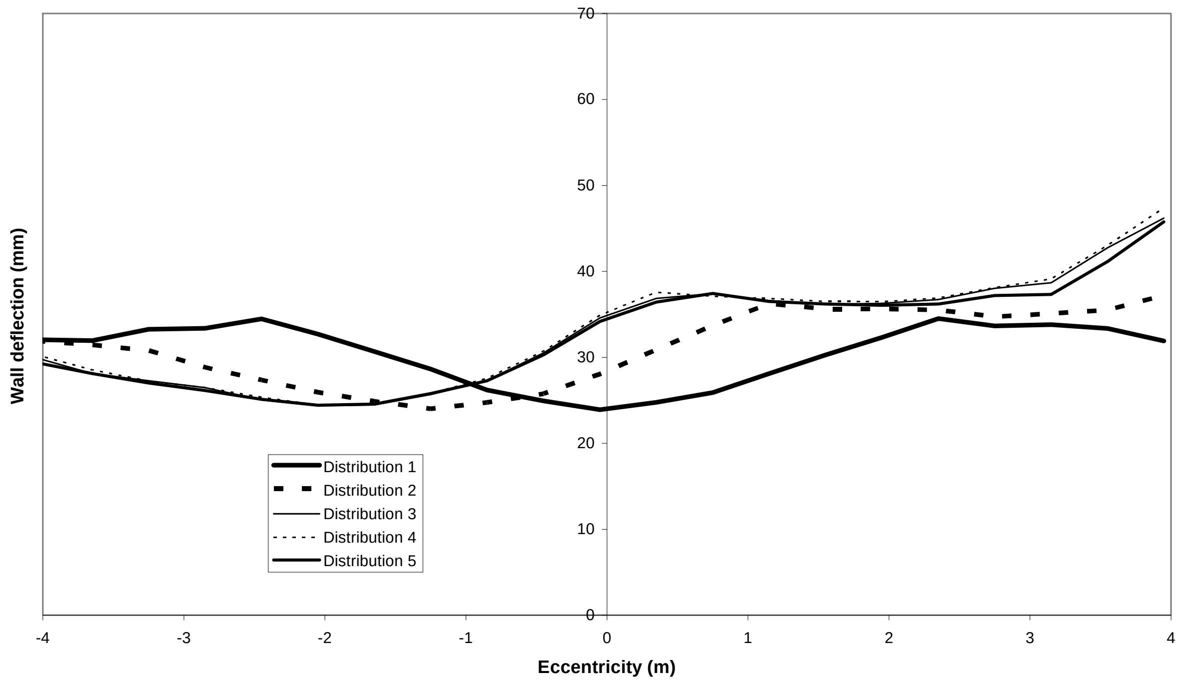


Figure 22. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for five SJT1 minimum bracing criteria wall resistance distributions*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

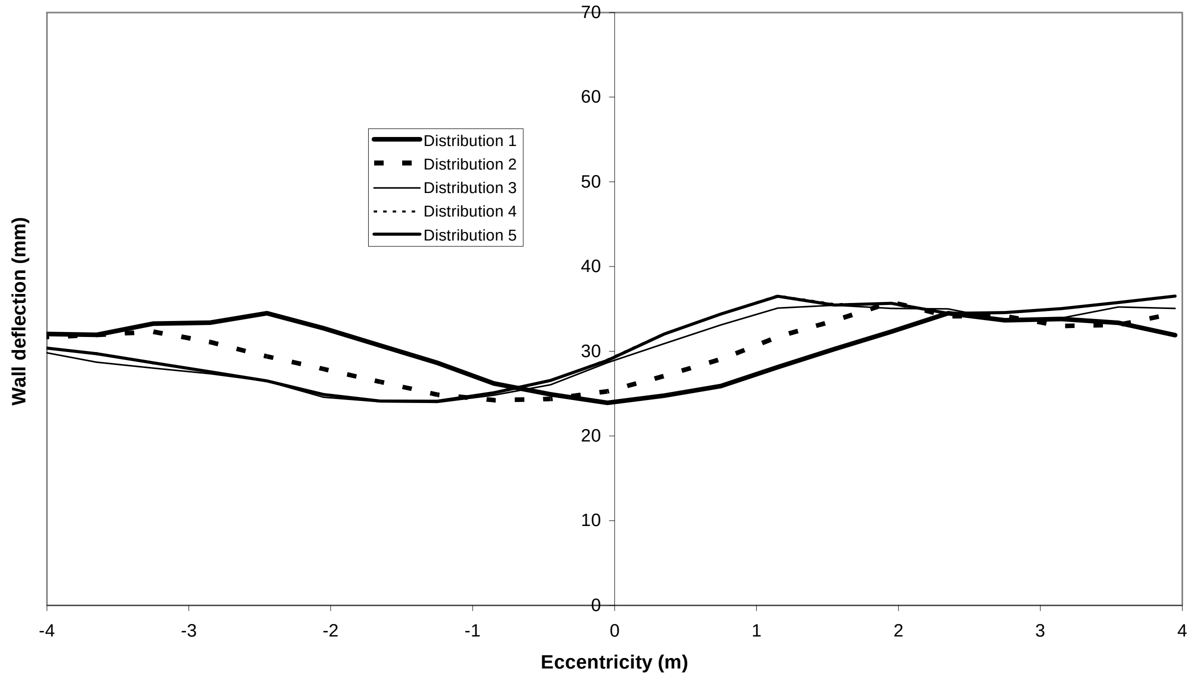


Figure 23. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for five SJT2 minimum bracing criteria wall resistance distributions*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

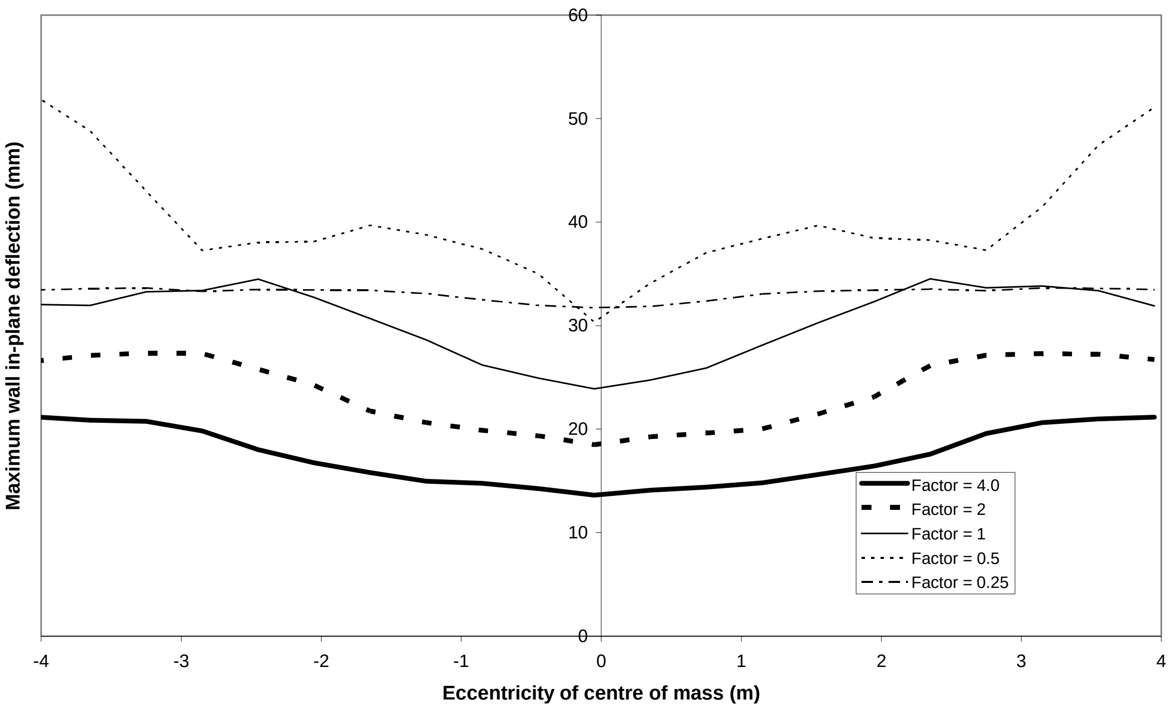


Figure 24. Sensitivity of house response to K_0.

- *Plots are given for four K_0 factors*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*

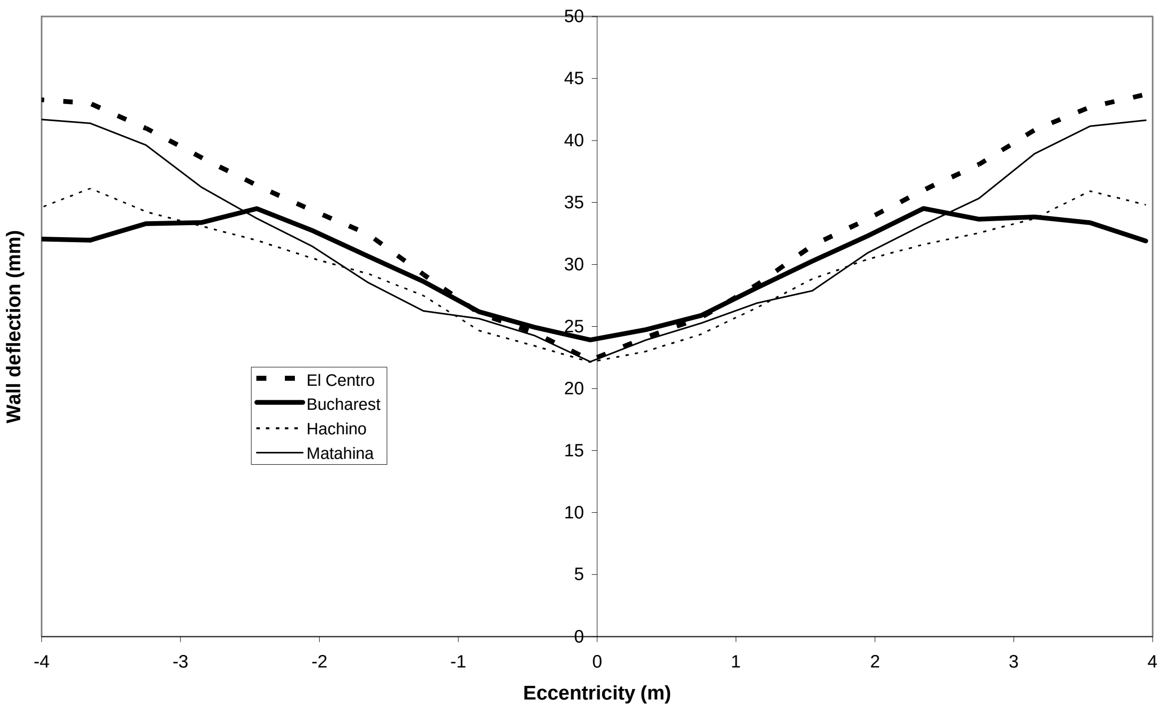
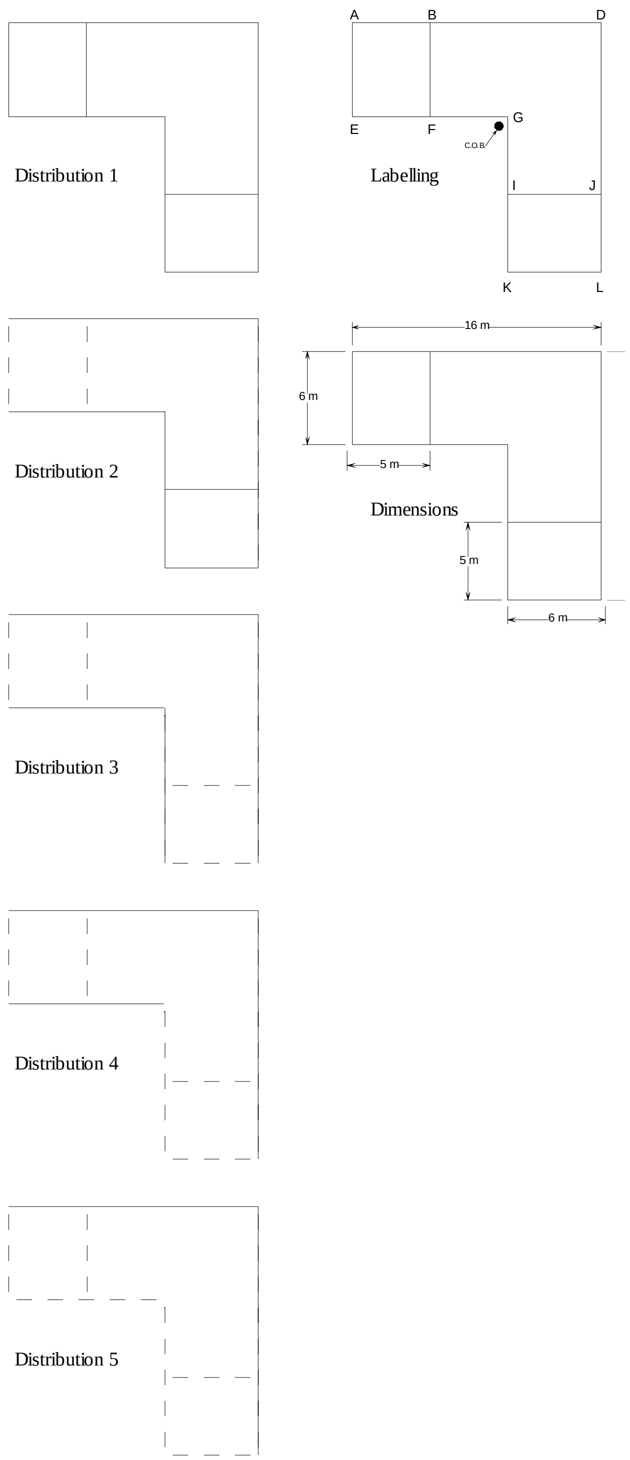


Figure 25. Sensitivity of house response to earthquake type.

- *Plots are given for four earthquakes*
- *The model is the single storey idealised house*
- *N-S earthquake excitation*



The dashed lines represent the walls which are assigned the reduced strengths given in Section 1.1 for the NZS 3604 criteria and Section 1.2 for the writer's criteria.

Figure 26. Distribution of wall stiffnesses for computer runs using minimum wall strength based on torsional criteria.

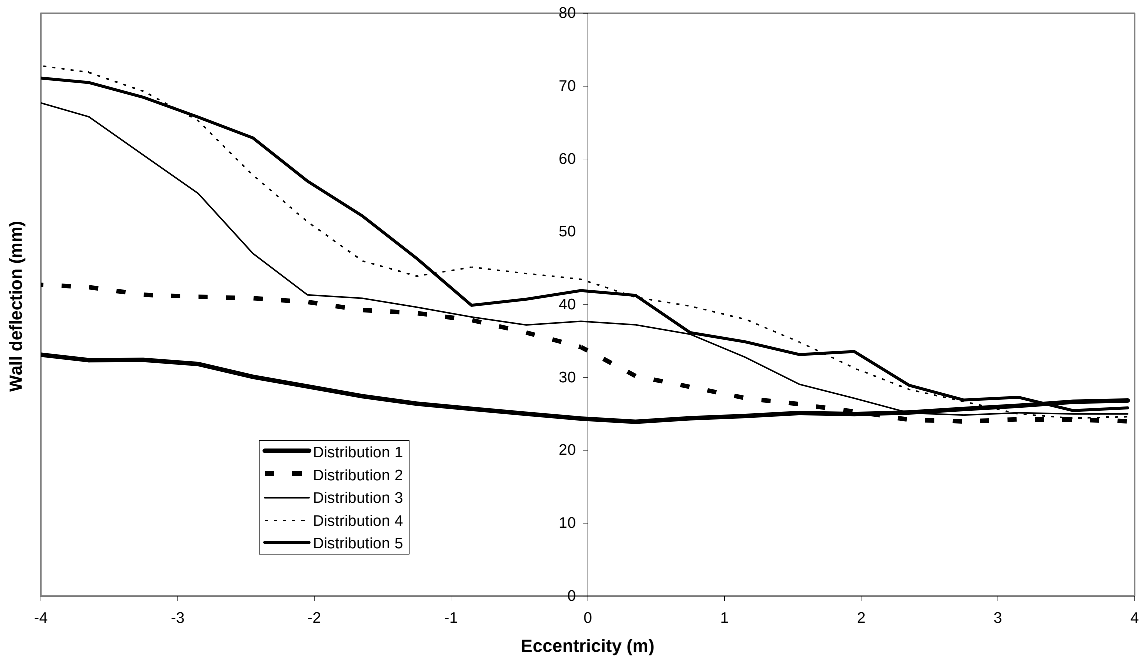


Figure 27. Maximum wall in-plane movement versus mass eccentricity.

- *Plots are given for five NZS 3604 minimum bracing criteria wall resistance distributions*
- *The model is the "L"-shaped house*
- *N-S earthquake excitation*

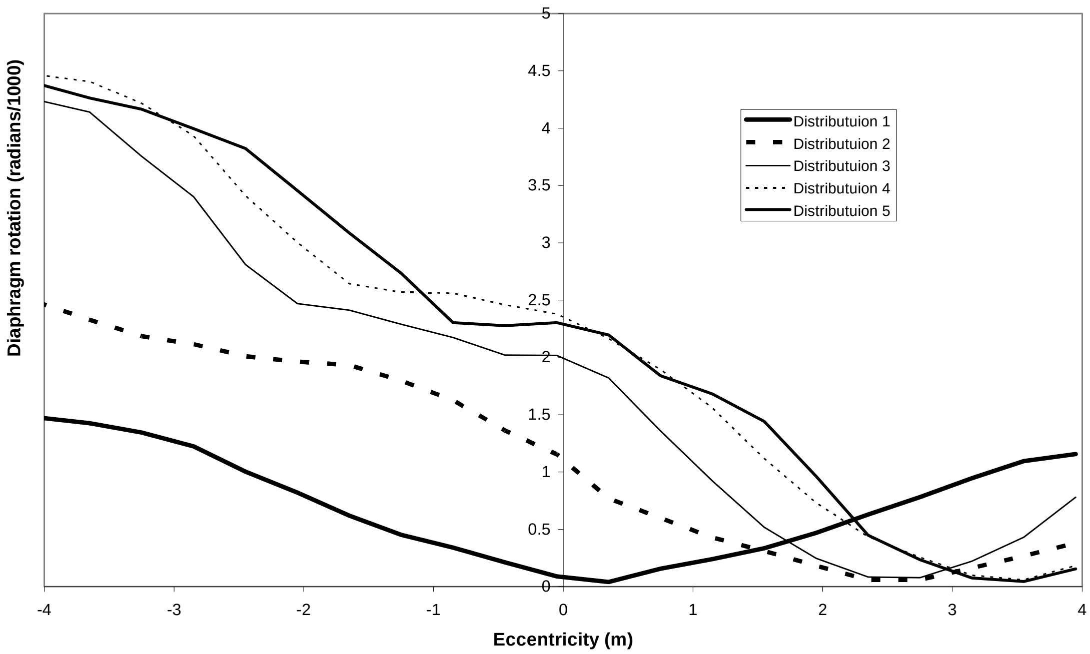


Figure 28. House rotation versus mass eccentricity.

- *Plots are given for five NZS 3604 minimum bracing criteria wall resistance distributions*
- *The model is the single storey "L"-shaped house*
- *N-S earthquake excitation*

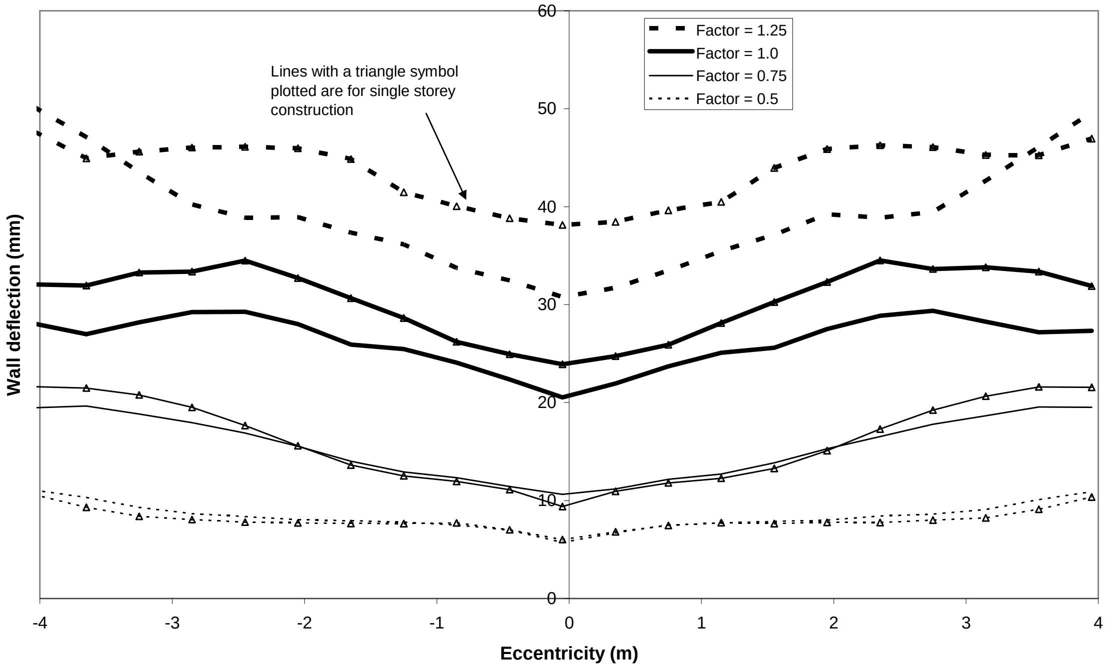


Figure 29. Comparison of the maximum wall in-plane movement for the two storey and single storey idealised house.

- *Plots are given for four earthquakes*
- *N-S earthquake excitation*

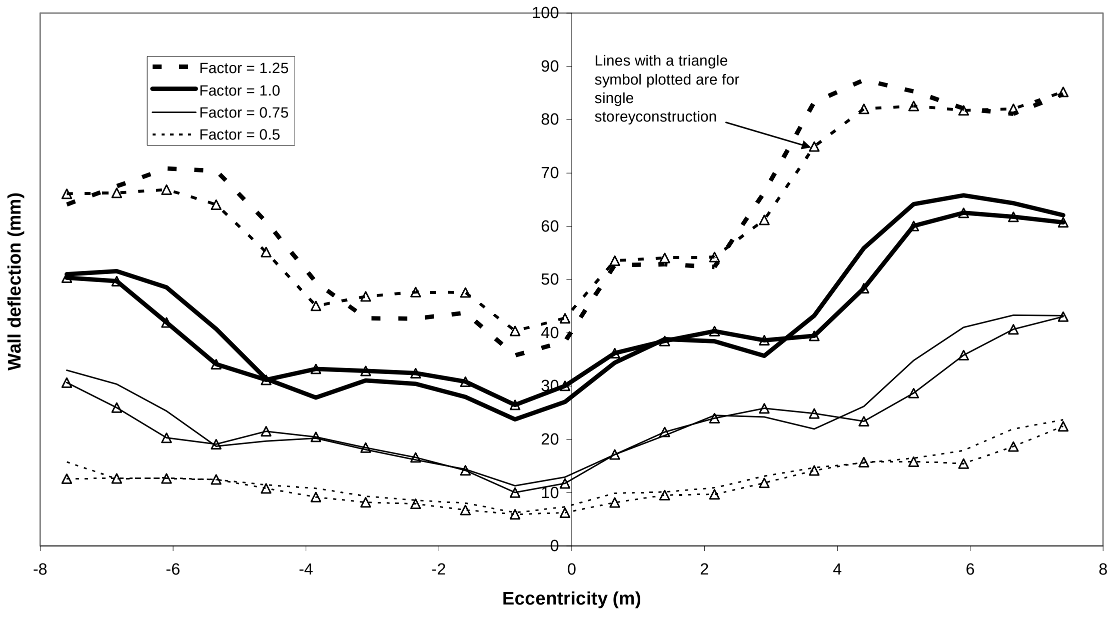


Figure 30. Comparison of the maximum wall in-plane movement for the two storey Alf house with those for the single storey Alf house.

- *Plots are given for four earthquakes*
- *N-S earthquake excitation*

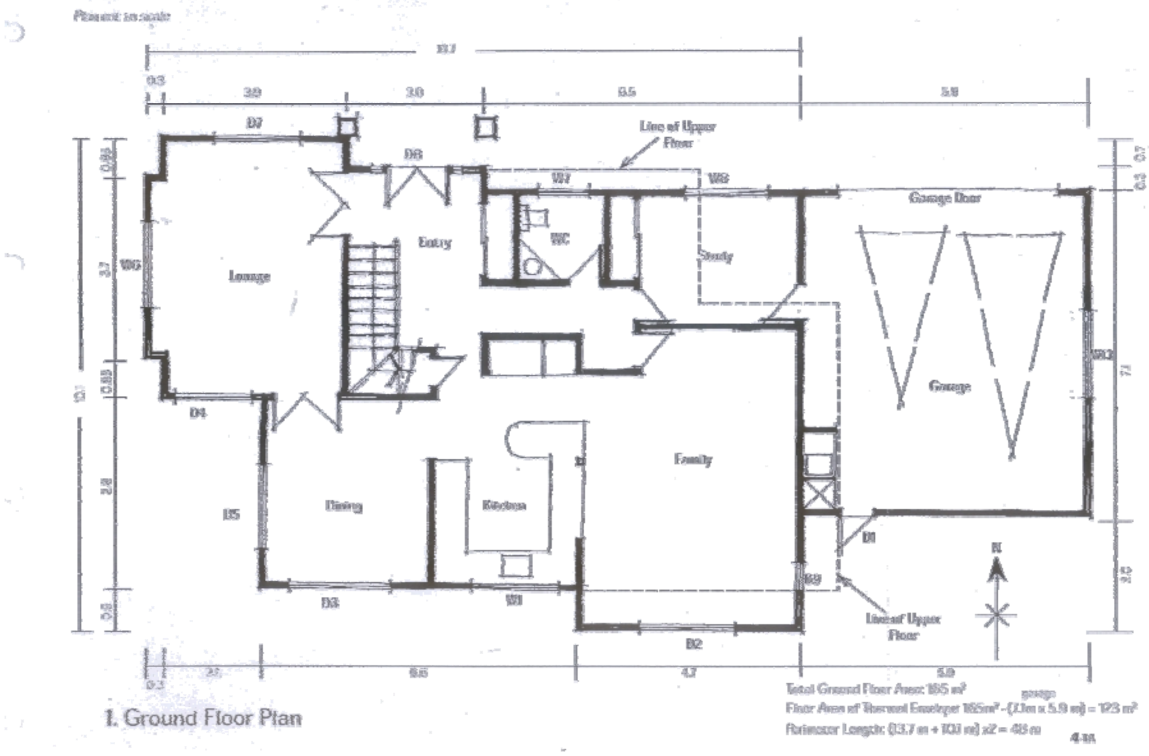


Figure 31. Plan view of the Alf house.

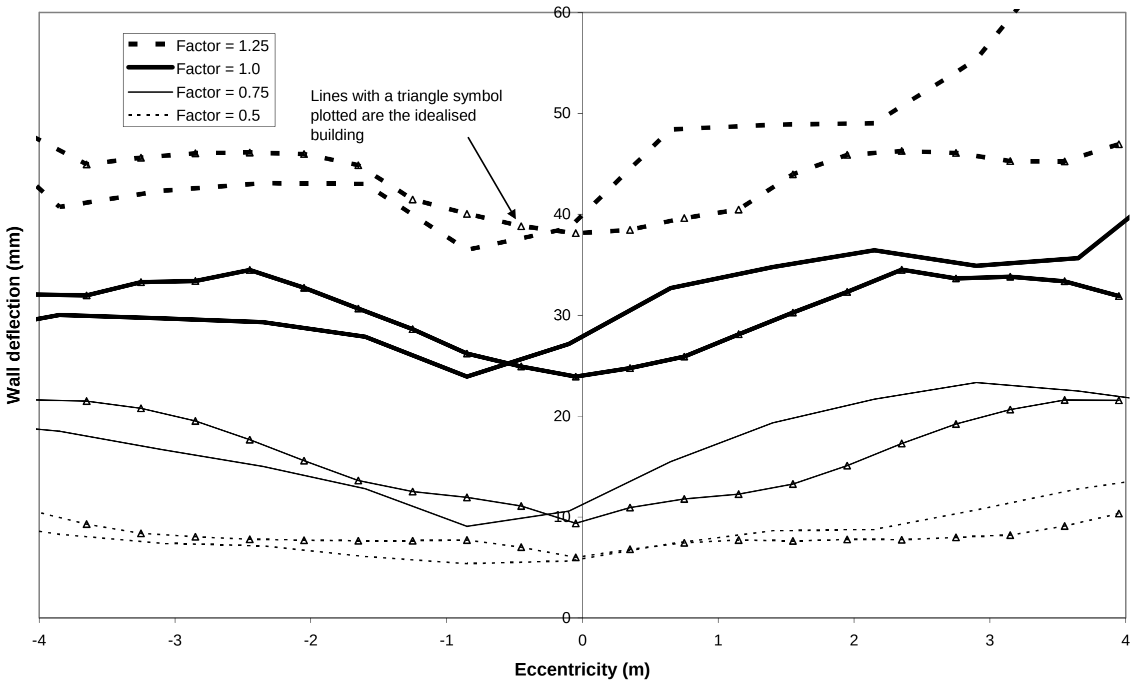


Figure 32. Maximum wall in-plane movement for single storey houses – comparison of the Alf house and idealised house.

- *Plots are given for four earthquakes*
- *N-S earthquake excitation*

9. CONCLUSIONS

NZS 3604 is the standard used to design most New Zealand houses (SNZ 1999). It does not require specifically constructed diaphragms at floor/roof levels provided the spacing of bracing lines does not exceed 5 m. In fact the spacing can be 6 m if a double top plate is used. In practice most New Zealand houses do have effective ceiling/floor and/or roof diaphragms. However, tiled ceilings without a good floor diaphragm and tiled roofs without ceilings will provide little diaphragm strength. Unless a house has adequate diaphragms walls will tend to attract load on a tributary area basis rather than as a function of their stiffness as assumed in the analysis used in this report. These situations are currently fairly rare and are ignored in this report.

Provided a house has effective diaphragms at each floor/roof level all house walls (irrespective of orientation) will help to resist a house from twisting under lateral wind or earthquake loading. NZS 3604:1999 stipulates a minimum wall bracing resistance which is intended to prevent excessive house twisting. Such twisting will generally increase maximum wall deflections and hence increase damage, and in the extreme situation perhaps result in collapse.

9.1 Houses without floor diaphragms

NZS 3604 has a separate set of wall strength distribution criteria for construction which it describes as “Floor diaphragms”. The conclusions of this subsection are for the situation where this does not apply – which is the norm.

The results presented in this report showed that placement of minimum strength walls allowed by NZS 3604 in both directions can result in excessive deflection. The minimum values do not relate to the house bracing demand forces i.e. do not increase for houses with heavy roofs/walls, houses in high earthquake zones, or for two as against one storey construction. In addition the minimum bracing rating for internal walls do not increase as the plan size of the house increases. The writer’s proposed distribution described in Section 1.2 does take these considerations into account. Use of this distribution resulted in acceptable deflections. Thus, it is recommended that the writer’s proposed minimum wall stiffness distribution described in Section 1.2 replace that currently stipulated in NZS 3604 (SNZ 1999). Note that the writer’s distribution assigns a minimum bracing as a function of bracing demand (unlike the current minimum) and ensures that the rating provided does not deviate too much from the tributary area approach, thereby providing some protection on diaphragm overload. Computer analysis using 1.5 x the writer’s minimum distribution showed still further reduction in wall deflections, but is considered to be too conservative.

An imbalance between locations of bracing walls and the location of lateral forces will increase diaphragm stresses. This effect has not been considered in this report.

9.2 Houses with floor diaphragms

Houses with floor diaphragms to Section 5.4.2.2 of NZS 3604 have not been modelled under time-history earthquake computer simulation in this study. However, in Section 1.3 of this report the writer proposes a minimum wall bracing bounding diaphragms by considering equilibrium of a diaphragm which encompasses an entire house. A revised minimum bracing rating for this type of construction is also proposed.

10. REFERENCES

[1] Standards New Zealand. 1999. NZS 3604 *Timber Framed Buildings*. SNZ, Wellington, New Zealand.

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