A Displacement – Focused, Force – Based Structural Design Procedure

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ABSTRACT: Procedures for designing structures to resist earthquakes have evolved from those used to design for other environment loadings. The force-based procedure commonly used for seismic design requires the designer to apply a set of forces to the structure, detail it to have adequate strength and check that the structure and its components have adequate deformation capacity.

A more rational design procedure is proposed in this paper that focuses on the deformations that result form ground movement beneath the structure. The deformation capacity of the structure and its components are checked first. Once the deformations are acceptable, the equivalent-static design forces are applied to the structure and the components are detailed to have adequate strength.

1 INTRODUCTION

Much of the cutting-edge research in the seismic design of structures is focussing on the development of displacement-based design procedures. There are arguments for and against using displacement-based procedures, but one significant disadvantage of these procedures is that they are not in current standards. Moreover, their absence from the recently published Earthquake Actions part of the Structural Design Actions Standard, NZS 1170.5 (SNZ 2004), means that they are unlikely to be in general use for at least the next five to twelve years.

The so-called force-based method has been used extensively for many decades, but it focuses the designer’s attention on calculating a set of forces that are to be applied to the structure. Whilst not the intention, even its name naively implies that forces represent those forces that the structure will be subjected to during an earthquake.

The proposal to use a displacement-focused force-based design method is attractive because it refocuses the designer’s attention on the important aspects of ground movement and building response that need to be considered for seismic design. These aspects include:

1. The ground movement beneath the structure causes it to deflect relative to its base.
2. The maximum building deflection is related to the earthquake motion and the building period
3. The building has to be strong enough to accommodate the deformation without collapsing.

Interstorey drift limits the deformations of many buildings and is therefore an appropriate focus from the start of the design process rather than a check at the end.

The light timber-framed buildings standard, NZS 3604 (SNZ, 1999), utilises this methodology in a rudimentary manner for house design, although this is not explicitly stated within either NZS 3604 or its supporting documents. The provisions of Section 5 of NZS 3604 have the designer calculate a bracing rating (demand) and then provide bracing elements with a total resistance that exceeds the demand. The types of construction materials and the location of the house are used to estimate the mass per unit area. The demand per unit area is tabulated in NZS 3604 for a range of locations and materials. The tabulated demand is multiplied by the plan area to give the required bracing strength

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that is required. Bracing elements are then added to the building until their combined rating (strength) is greater than the required rating (demand).

The NZS 3604 method, as a force-based method, assumes that all of the buildings have the same natural period (0.4 sec), which will produce different deformation demands in different locations as will be shown later.

The displacement-focused force-based design procedure outlined in the next section was developed to provide a guideline for students taking a final-year B.E. course entitled Structural Concepts. It is a preliminary or hand design procedure, that is more to give the students an overview of the design process and to understand how structures respond to ground movement than to provide a step-by-step procedure to follow in a design office. The preliminary design procedure is presented in the next section. This is followed by a description of the dynamic response of buildings and the displacement spectra from NZS 1170.5. The final section presents some software tools that designers could use to implement the conceptual design procedure.

2 DESIGN PROCEDURES

Design procedures, by their nature, depend on the analysis methods used by the designer. They also depend upon the tools, such as a spreadsheet or software package, that the designer uses to analyse the structure. The proposed design procedure describes the steps that would be used in a preliminary or hand design method. Design using more practical software tools is described later.

Before presenting the design procedure, is helpful to systematically label the items being designed to minimise confusion. The structural floor plan shown in Figure 1 (Paulay 2000) shows wall elements composed of one or more components and frame elements with the column components circled. The column components within a multi-storey building are further subdivided into segments but a beam component is only considered to begin and end at the column faces within a single bay. The displaced position of the roof is also shown with dashed lines in the figure, alongside the equivalent-static earthquake design force, V_E, that acts through the centre of mass (CM) to cause the deformation.

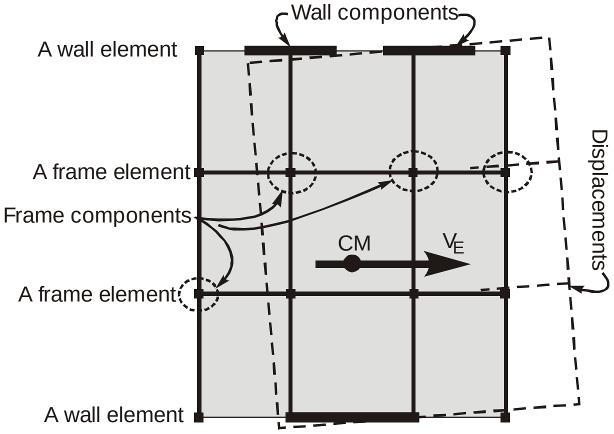

Figure 1 Elements and components within a structure, shown in plan view (Paulay 2000).

Most New Zealand buildings are probably analysed using equivalent static forces because the model is easily defined and the design procedure is conceptually simple. Also, there should be fewer design errors when the designer understands what he or she is doing. There is more room for error with more sophisticated analysis methods that have a myriad of additional analysis options and assumptions[1].

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[1] Specifically, the author's opinion is that multi-modal analysis is useful for understanding how a building responds to ground motion in a general sense. Designers shouldn't resort to using sophisticated analysis methods to circumvent design compromises in a structure, particularly if it will be occupied by humans. The reliability of the analysis methods is probably similar but there is significantly more potential for designer error.

The commonly used design procedure is iterative because the deflections and component deformation capacities are checked at the end but changing the component properties at this stage affects the stiffness and therefore the initially assumed fundamental period. Moreover, the structural ductility factor needs to be assumed and then checked. Experienced designers will require less iteration because they will use better estimates for their preliminary design

The equivalent static design method requires good guesses of both the dimensions of all the elements in the structural system and their strengths to avoid iterating through the design procedure more than once. In essence, this requires a preliminary design prior to the detailed design.

2.1 *Displacement-Focused Force-Based Design Procedure*

Paulay (2000) proposed a rational “Displacement Focused” design method that reorders the design steps to begin with displacements. It is a “design method” in that the structure is designed without requiring sophisticated computer analysis of the structural response in the elastic range that is then projected to the in-elastic range.

The conceptual steps in the proposed design procedure are:

1. Choose a lateral-load resisting system that makes the structure as regular as possible.
2. Select the materials you will use, the most important property is the steel yield stress.
3. Choose a suitable inelastic deformation mechanism for the structural system, checking that other parts of the structure don’t compromise the chosen deformation mechanism.
4. Estimate the dimensions of the components and elements in the structural system.
5. Calculate the seismic weight of each floor within the structure.
6. Calculate the nominal yield curvatures for the structural elements, based on their yield strengths and in-plane widths and depths.
7. Assume a base shear of unity and distribute it over the height of the structure.
8. Assume a strength distribution between the elements (in plan), which positions the centre of strength close to the centre of mass.
9. For each element, calculate its:
    a. Yield displacement at the height of the effective mass (i.e. at about 2/3 of structure height);
    b. Nominal stiffness;
    c. Displacement limit at the height of the effective mass;
    d. Drift limit anywhere within its height.
10. Calculate the displacement limit, Δ_{lim}, for the structure at its centre of mass. This is usually based on the displacement limit or drift limit of the element with the greatest stiffness at the edge of the structure that has the greatest displacement.
11. Calculate the yield displacement, Δ_y, and displacement ductility, μ ($= \Delta_{lim} / \Delta_y$), of the structure.
12. Estimate how much additional displacement will be contributed by P-Δ actions. Divide this by the displacement ductility and subtract it from the yield displacement, Δ_y, to give the design spectral displacement, SD.
13. Estimate the fundamental period, T_1, of the structure from the NZS1170.5 displacement spectrum, using the calculated values of SD and μ.
14. Calculate the base shear from the NZS1170.5 horizontal design action coefficient.
15. Distribute the base shear force into design actions for each level of each of the elements.

16. Detail each of the element’s components to have sufficient strength to resist their own design actions.
17. Calculate the displacements for each element due to the combined design and P-Δ actions and check that these are acceptable. (Use Method B of NZS 1170.5 to calculate the P-Δ actions.)
18. Detail the damage regions within the elements (or their components) to resist the structural actions.
19. Detail the remainder of the structure to accommodate the anticipated deformations and resist any overstrength within the damage regions.

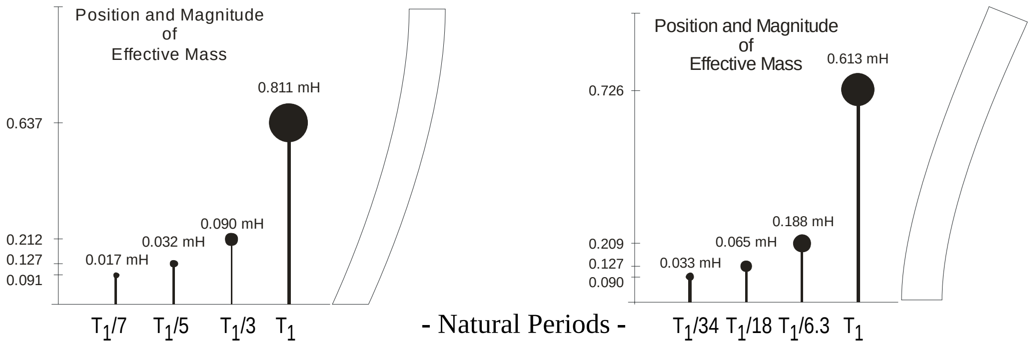
Most aspects of steps 1 to 5 and steps 14 to 19 in this procedure are similar, but possibly in a different order, to those that would be used for the traditional force-based method. These are covered by the provisions NZS 1170.5. Paulay (2000) gives details of the methodology of steps 6 to 11, which will not be reproduced here because of the limited space.

3 DISPLACEMENT SPECTRA

In keeping with the focus on structural displacements, it is helpful to briefly review how a structure deforms in response to ground motion and then look at how the deformation is used by the structural designer.

Structures vibrate in response to ground motion. A structure normally has many natural periods of vibration, and each amplifies the portion of the ground motion that it is “tuned” to respond to. Each natural period of an elastically responding structure has an associated deformation pattern or mode shape that, like its period, is related to the vertical distribution of mass and the arrangement of the structural elements. This gives the deformed shape of each mode. The magnitude of the deformations for each mode is obtained using the spectral displacement (SD) of an equivalent single-degree-of-freedom oscillator. This is the basis of the modal analysis method, which superimposes the (elastic) modes to obtain the total response.

The equivalent single-degree of-freedom oscillators for the first four modes are shown in Figure 2 (in decreasing mode number) for a tall, elastically responding building with its mass (m) and stiffness uniformly distributed over its height and braced using either moment frames or using structural walls. The effective mass shown in Figure 2 for each mode is used to determine the base shear for that mode and its position, as a portion of the total building height, H, on the vertical axis, determines the overturning moment. The deformed shape of the fundamental modes is illustrated to the right of each figure.



a) b)

Figure 2: The positions and magnitudes of the effective mass in a) a tall shear building braced using frame elements and in b) a tall flexural building braced with wall elements.

The fundamental mode produces the greatest portion of the deformation for both types of structure, with the equivalent single-degree of-freedom oscillator for that mode having between 60 and 80 percent of the total building mass that is located at between 2/3 and 3/4 of the total height. The natural periods for the first for modes are given as a portion of the fundamental period, T_1, in Figure 2 for both types of building.

The design actions used in step 15 of the proposed design procedure induce greater structural displacements than the first mode because they apply the full base shear to the structure. The fundamental mode has less effective mass, so the displacements need reducing. Displacements are reduced by a factor of 0.85 for 6 storeys or more when using the provisions in section 6.3 of NZS 1170.5 (which may be conservative for flexural structures as shown in Figure 2b). However, the maximum interstorey displacements predicted using either analysis method are less than those obtained using time-history analysis, so the interstorey displacements are increased by a factor of 1.2 to 2.5 before checking that they don't exceed the permissible 2.5 % (sections 7.3 and 7.5 of NZS 1170.5).

The magnitudes of the building displacements for an elastically responding structure depend upon the spectral displacement. This is plotted as functions of the natural period for the four major New Zealand cities in Figure 3. These were derived from the spectral accelerations published in NZS 1170.5. A second plot is included for Wellington, for an impossible distance of D > 20 km from an active fault, for comparison with the displacements for the other two cities.

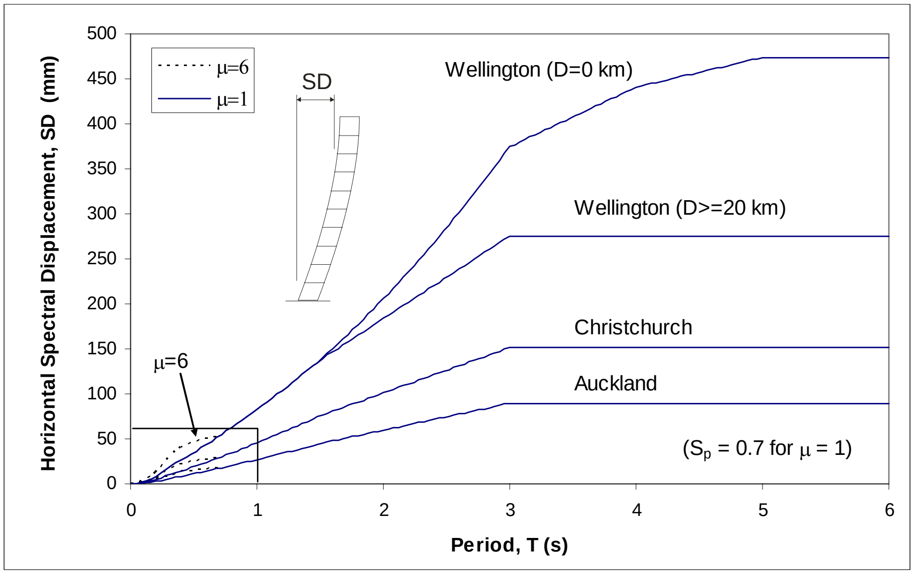


Figure 3. Horizontal spectral displacements for structures founded on Class C (shallow) soils in Wellington, Christchurch and Auckland.

The Figure 3 elastic spectral displacements have a structural performance factor of $S_p = 0.7$ for comparison with the inelastic response spectra, which, in accordance with the equal-displacement rule, all have the same displacement as an elastically-responding structure for $T_1 > 0.7$ sec (for Class C soils). Structures that are designed to remain elastic will have a greater deformation because they need to use $S_p = 1.0$.

The lower strength limit of between $0.03R_u$ and $0.04R_u$ for most structures, where R_u is the risk factor, is not included in Figure 3 either. If it was, the displacements would increase as a square of the period increase, which is not realistic when the limit is primarily to provide a minimum structural strength, which shouldn't affect deformations.

The more universally recognisable design action coefficients, Cd(T), for the three Figure 3 cities are plotted in Figure 4. The inelastic spectra (only plotted for Auckland to avoid congestion) show the $0.3R_u$ limit (for Auckland) effectively restricts the ductility that can be usefully employed in Auckland structures.

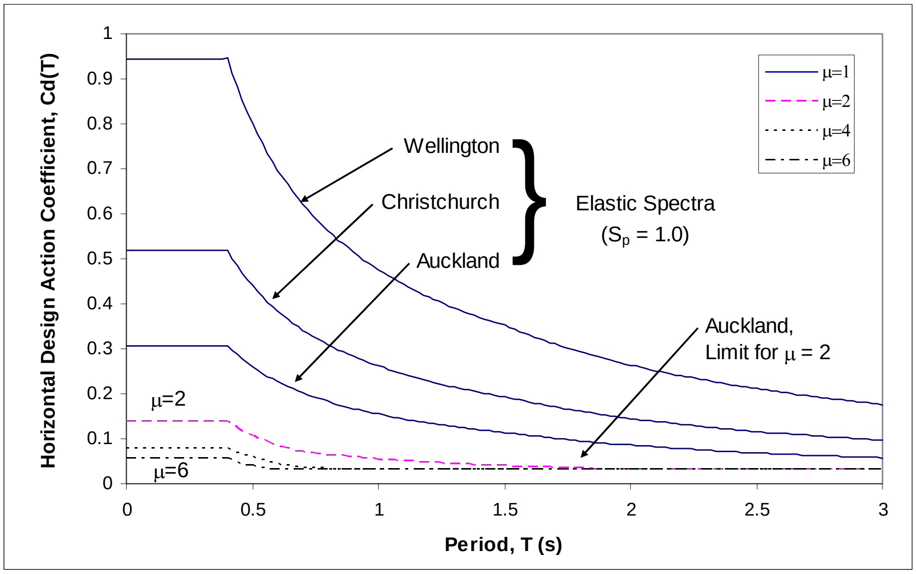


Figure 4. Horizontal design action coefficients for structures founded on Class C (shallow) soils in Wellington, Christchurch and Auckland

For periods of less than 0.7 sec (for Class C soils), the displacement demands for an inelastically-responding structure are greater than they are for an elastically responding structure with the same natural period. The displacement demands for periods of up to 1 second are plotted in Figure 5. This shows that the inelastic displacement demands for μ = 6 are likely to be fifty six percent greater than those induced in an elastically-responding structure for periods less than 0.4 sec.

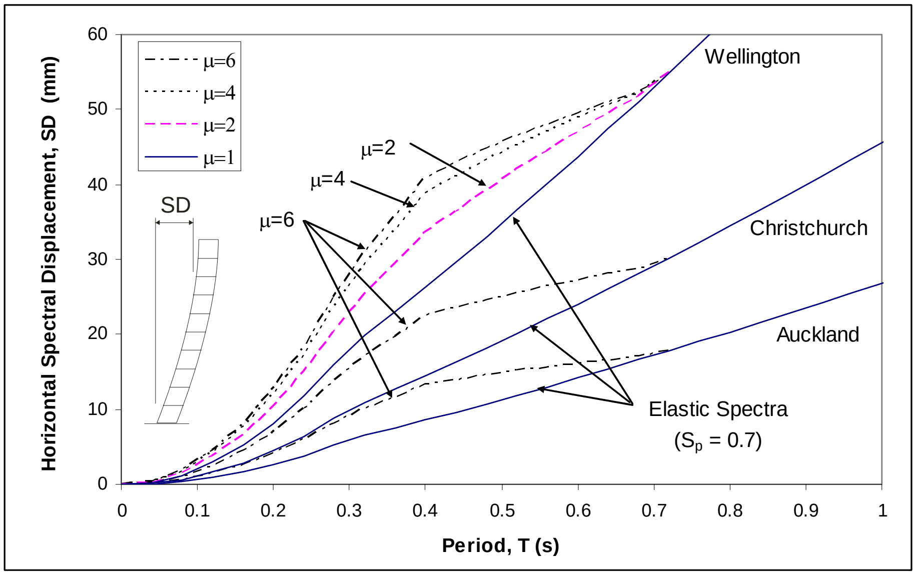


Figure 5. Horizontal elastic and in-elastic spectral displacements for structures founded on Class C (shallow) soils in Wellington, Christchurch and Auckland.

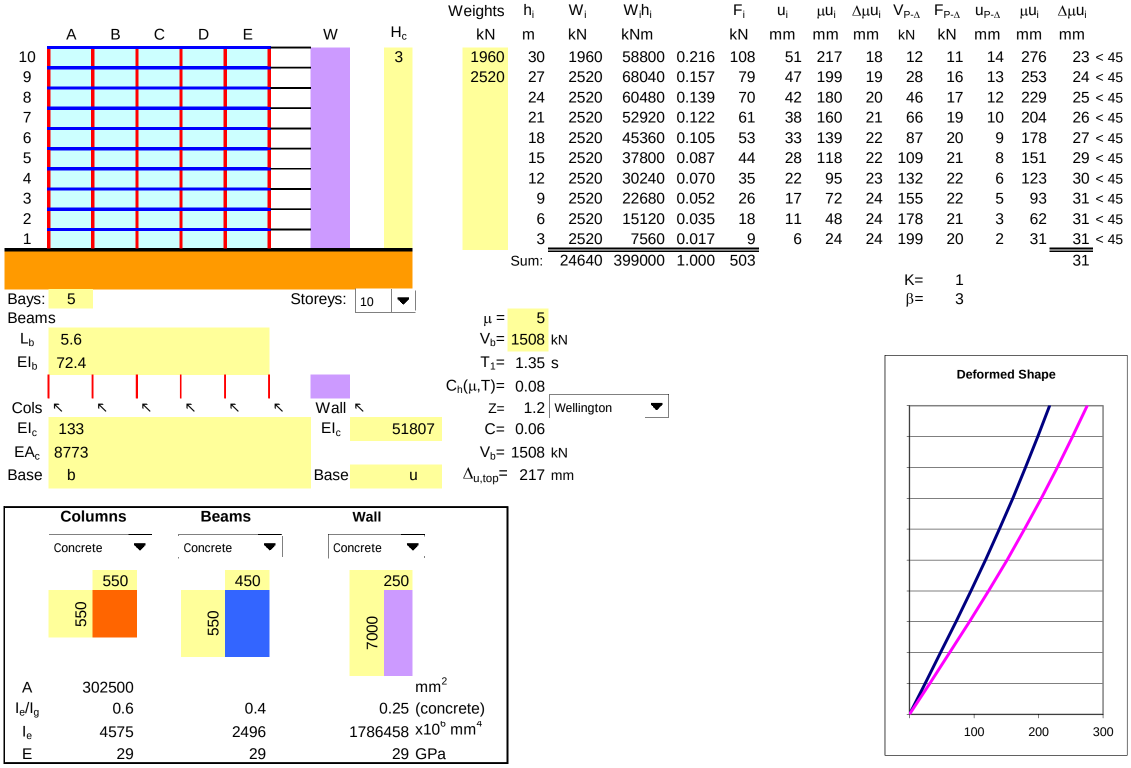
4 DESIGN TOOLS

The designer requires a considerable amount of interaction with the structural analysis software in the course of applying the design procedure. Analysis tools, such as software packages, normally focus more on performing the analysis (i.e. input data and results, either graphically or text-based) and leave the user to develop their own design procedure, transferring data between the software and a spreadsheet (or calculation pad) for recording other calculations as needed. There are a large number of software packages that were primarily developed to analyse structures, but have been adapted to provide a more useful tool for designers.

Charleson’s *Resist* 3D modelling software (1993) changes the focus from the analyst to the designer. Resist is a very useful tool for preliminary structural design and for conceptually understanding how structural bracing systems work. While its primary objective appears to be for Architects to select the type and position of bracing elements, it can also display more detail of its calculations that can then be used by a Structural Engineer.

A Microsoft Excel spreadsheet was developed by the author for structural engineering students to understand force-based design. Like *Resist*, the spreadsheet provides immediate numerical and graphical feedback of deformations and forces as the structural dimensions and properties change. The spreadsheet models one of three identical lateral load-resisting elements within a building braced by a frame, a wall or a frame and wall. The building can have between up to ten storeys and the frame can have up to five bays. A range of column base (or foundation) options are provided, including pinned bases, fixed bases, base-isolators that are flexible in shear and foundation beams that are the same as the other beams. The wall can also be base-isolated or can be completely removed.

The spreadsheet has a worksheet for force-based design and a second for modal analysis. A screen shot from the ‘force-based design’ worksheet is shown in Figure 6. On the spreadsheet, the student can select the number of storeys and frame bays (beneath the top left colour graphic) and can either enter the section properties for the beam, column and wall components (centre left) or enter the member designation (steel) and cross section dimensions (concrete beams and walls, both lower left) in the shaded regions. A range of column base (or foundation) options are provided, including fixed, base-isolators and foundation beams.



Weights kN	h_i m	W_i kN	W_ih_i kNm		F_i kN	u_i mm	μu_i mm	$\Delta\mu u_i$ mm	$V_{P\text{-}\Delta}$ kN	$F_{P\text{-}\Delta}$ kN	$u_{P\text{-}\Delta}$ mm	μu_i mm	$\Delta\mu u_i$ mm	
1960	30	1960	58800	0.216	108	51	217	18	12	11	14	276	23	< 45
2520	27	2520	68040	0.157	79	47	199	19	28	16	13	253	24	< 45
	24	2520	60480	0.139	70	42	180	20	46	17	12	229	25	< 45
	21	2520	52920	0.122	61	38	160	21	66	19	10	204	26	< 45
	18	2520	45360	0.105	53	33	139	22	87	20	9	178	27	< 45
	15	2520	37800	0.087	44	28	118	22	109	21	8	151	29	< 45
	12	2520	30240	0.070	35	22	95	23	132	22	6	123	30	< 45
	9	2520	22680	0.052	26	17	72	24	155	22	5	93	31	< 45
	6	2520	15120	0.035	18	11	48	24	178	21	3	62	31	< 45
	3	2520	7560	0.017	9	6	24	24	199	20	2	31	31	< 45
	Sum:	24640	399000	1.000	503								31	

K= 1
β= 3

Bays: 5
Storeys: 10
Beams
L_b 5.6
EI_b 72.4
Cols
EI_c 133
EA_c 8773
Base b
Wall
EI_c 51807
Base u

μ = 5
V_b= 1508 kN
T_1= 1.35 s
$C_h(\mu,T)$= 0.08
Z= 1.2 Wellington
C= 0.06
V_b= 1508 kN
$\Delta_{u,top}$= 217 mm

	Columns	Beams	Wall	
	Concrete	Concrete	Concrete	
	550 × 550	450 × 550	250 × 7000	
A	302500			mm^2
I_e/I_g	0.6	0.4	0.25	(concrete)
I_e	4575	2496	1786458	$x10^6$ mm^4
E	29	29	29	GPa

Figure 6. A Microsoft Excel spreadsheet for preliminary design of wall and frame bracing elements.

The seismic design information is entered and displayed in the middle of the worksheet and the design forces and deformations at each level are tabulated (top right) and plotted (lower right). P-Delta forces and deformations are also calculated and plotted. (Figure 6 shows the significantly larger deformation that can occur when P-Delta forces are included in the analysis.) The whole worksheet prints out on a single A4 page as a record of the calculations. The modal analysis worksheet has a similar layout. That worksheet displays the mode shapes for all of the structural modes and calculates the applied actions and displacements for individual modes and for combinations of modes.

The visual feedback helps the students to develop a feel for what happens in the building. One exercise gets the students to vary the structural properties to investigate the effects of things like one higher storey height, a reduced or increased roof weight, changing the beam and column stiffness, changing the wall stiffness, the different column and wall foundation bases. The significant effects that sometimes seemingly minor changes can have on mode shapes provide a good illustration of why engineers prefer regular buildings!

Tools like this spreadsheet illustrate how the “design procedure” outlined earlier needs to vary to accommodate the analysis tool employed by the designer. The proposed design procedure provides a series of steps but when using an “overview” tool like this, the designer can see what is critical and modify the structure to correct the problem, even if it is not the next step in the procedure. The spreadsheet deliberately avoids displaying design actions for the components so the student designers can understand how the building responds rather than get lost in details. It is deliberately 2D for the same reason. Of course, this relies on the idea that mastery of what happens in 2D should give them a better chance of understanding 3D behaviour.

5 CONCLSIONS

A displacement-focused force-based design procedure has been presented which outlines the conceptual steps required to design a structure. The procedure focuses on deformations rather than forces, although the latter are still important aspects of designing the structural elements and components. It should provide a framework that will be useful until we have reliable displacement-based design procedures. A spreadsheet for students has been presented as an illustration of how the steps in the design procedure can vary when a different analysis tool is employed.

The concepts and details of displacement spectra have been presented using values from the recently published Part 5 of the Structural Design Actions standard, NZS 1170.5 to assist designers to develop a feel for the magnitudes of displacement demands in different locations.

6 ACKNOWLEDGEMENTS

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