The displacement paradox for seismic design of tall timber buildings

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ABSTRACT: Design to control displacements is becoming increasingly important in seismic design of buildings, to reduce the potential costs of structural and non-structural damage, accentuated by observations from the 2010-2011 Canterbury earthquakes. The damage potential of displacement is far beyond the damage potential of force, however displacements are too often overlooked.

The displacement paradox occurs because, on the one hand, designers need to control lateral displacements to reduce damage and the possibility of structural collapse, but on the other hand, they must provide enough displacement to activate non-linear response and thereby reduce seismic forces. These two objectives sometimes clash, creating a paradox. There is a danger that an "improved" design process to reduce accelerations and seismic forces can lead to "poorer" behaviour because of increasing displacements which will cause unintended damage. For some building systems, this displacement paradox may make it very difficult to provide sufficient ductility in the seismic design of the building while still meeting lateral displacement limits.

Control of lateral displacements is especially important when using flexible structural materials like wood. Traditionally non-linear response of timber structures, as with most other materials, has been provided by its connections however these connections must be displaced enough to be non-linear.

Multi-storey timber buildings can achieve the same level of seismic performance as concrete or steel buildings, with careful design and attention to detailing, provided that lateral displacements are addressed properly.

1 INTRODUCTION

Design to control displacements is becoming increasingly important in seismic design. In recent years the public expectation of what is acceptable in seismic resisting construction has changed significantly. Engineers today live under demands which are far more intensive than their historical counterparts and recent seismic events have shown that preserving life is no longer sufficient, and a preservation of livelihood is now the minimum. This means that after a major seismic event a building should not only be intact but be usable with no or minimal post-quake intervention. The control of building displacements lies at the heart of this new philosophy with the reduction of displacement being the only true way to reduce the potential costs of structural and non-structural damage.

Seismic design codes such as NZS 1170.5 (NZS, 2004a) have very different displacement limits for Ultimate Limit State (ULS) compared with the Serviceability Limit State (SLS) loading conditions. The ULS limits are imposed to protect structural stability of the building, whereas the SLS limits given in the Commentary to NZS 1170.5 (SNZ, 2004b) are intended to control non-structural damage with regard to appearance, repair, and weather-tightness. Non-structural damage can also be caused by very high accelerations, but accelerations are not limited in the design codes.

Precise calculation of displacements is not always easy, and they are usually only checked late in the design procedure, unless displacement based design procedures are followed.

Timber buildings can achieve the same level of performance as concrete or steel buildings, with careful design and attention to detailing, but ductile design is only possible if there is a sufficiently large displacement window between onset of yield and the ultimate displacement limits. The increased flexibility of timber can limit this window.

2 THE "DISPLACEMENT WINDOW"

The "displacement window" is the difference in lateral displacement between the onset of yielding and the upper bound prescribed by codes to maintain structural stability. The larger the displacement window, the easier it is to ensure that the design level of in-elastic response will be provided by a structure under earthquake loading.

2.1 The upper bound of the displacement window:

The upper bound of the displacement window is the maximum code-specified displacement for ULS loading.

For ULS loading (Section 7 of NZS 1170.5), the principal deflection limit for ductile materials is 2.5% lateral drift (75mm inter-storey displacement for a 3.0m storey height), which is *"imposed to minimize the probability of instability through the development of soft-storey mechanisms"* (SNZ, 2004b). There are additional limits to prevent buildings from swaying over boundaries, to prevent pounding with adjacent buildings, and to avoid P-delta effects. The ULS limits are not intended to avoid or control non-structural damage.

The calculation of horizontal deflections and drifts is outlined in Section 7.2 and 7.3 of NZS 1170.5. Section 7.2 provides guidance on calculation of the deflections using elastic based methods (equivalent static or modal method) which are then modified to allow for the amount of in-elastic response desired from the structure with possible further modification for sidesway and P-delta effects. Inter-storey drifts are then calculated as per Section 7.3 with the additional allowance for the tendency of elastic-based methods to underestimate the contribution of higher modes to inter-storey drifts.

2.2 The lower bound of the displacement window:

The lower bound of the displacement window is the displacement at which yielding occurs. This depends heavily on the structural system, the structural materials, and the geometry of the structural members and connections. It can be reduced by increasing the stiffness of the lateral load resisting system, but this may be difficult or expensive for some structural timber systems.

2.3 Horizontal displacements for serviceability

For SLS loading, deflection limits are given in the Commentary to NZS 1170.5. The main standard, states that these deflections are "*limited so as not to adversely affect the required performance of other structure components"*, but in the Commentary, the limits for different components are specified to prevent cracks sufficiently visible to need repair or to prevent weather-tightness problems. These deflection limits range from H/600 (0.17% drift, or ~5mm) for unreinforced masonry to H/200 (0.5% drift, or ~15mm) for paper-finished gypsum board walls. These limits for SLS are essentially the same as those in Table C1 of AS-NZS 1170.0 (SNZ 2002), that are applicable to all loading conditions including wind loading. Most international codes have similar limits, independent of the structural materials. For example the Canadian code specifies a SLS limit of H/500 (0.2% drift, or ~6mm) for both wind and earthquake loading.

Further, more or less stringent, limits may be imposed by the designers of non-structural elements, which requires clear and honest dialogue between the structural engineer and the product provider.

The consideration of serviceability deflections imposes an additional restriction on the displacement window. Considering the above limits a structure may need to have increased stiffness on order to satisfy SLS displacement limits or in rare cases may require increased strength to prevent in-elastic behaviour under SLS loading. Increasing the initial stiffness will increase the displacement window by decreasing the displacement at which yield occurs as shown in Figure 1b.

It is important to note however that the considerations account solely for the system response and ignore the interaction between system response and earthquake demand.

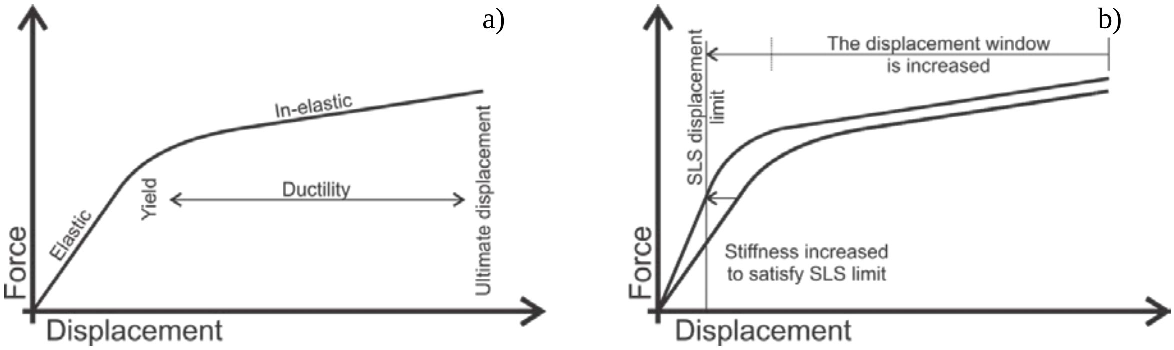

Figure 1. a) the displacement window and b) the impact of increase to satisfy SLS limits on the displacement window.

3 THE NEED FOR IN-ELASTIC RESPONSE

A very stiff building designed for only elastic response will be subjected to very high accelerations and high seismic forces. High seismic forces result in expensive buildings, and high accelerations lead to high levels of possible damage to contents. Engineers have two weapons against these high accelerations: ductility and damping.

All modern design codes for seismic areas use a force based design approach. This approach requires an assumption to be made regarding the initial period of the structure and the amount of ductility that the structure will possess at its performance point. It is normally then assumed that by providing a structure with ductility that it will also possess hysteretic damping. It is worth noting however that ductility, normally defined as the ratio between the ultimate displacement and the displacement at yield, influences seismic response separately from the influences of material hysteretic response.

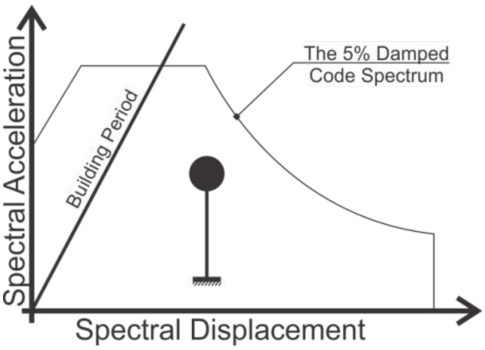

Figure 2. The ADRS Spectrum.

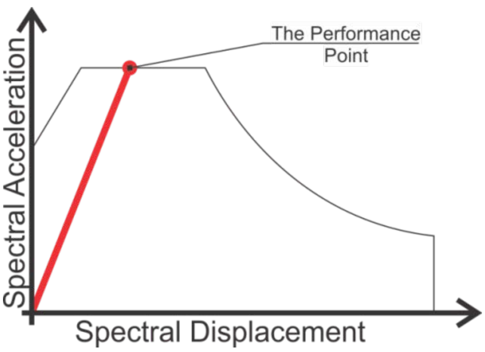

Figure 3. The structural capacity curve of an elastic SDOF.

To illustrate this point, a dimensionless Acceleration Displacement Response Spectrum of a single degree of freedom system will be used. The use of this spectrum allows the visualisation of the non-linear response of the non-linear SDOF system by presenting both the structural capacity (pushover) curve and the demand spectrum, plotting them in spectral-acceleration versus spectral displacement coordinates. As shown in Figure 2, period is represented on an ADRS spectrum as radial lines originating from the origin.

The code response spectrum is presented with a damping ratio of 5%. This is intended to represent the Elastic Damping of the structure. Elastic damping is used to introduce damping not captured by the hysteretic model represented by the codified reduction methods. This damping has a number of sources of which the most important is the typical simplification that the hysteretic model has a perfectly linear response in the elastic range. Damping can also result from impact damping, foundations and the interaction between structural and non-structural elements.

If a building remains elastic it will respond to earthquake loading as shown in red in Figure 3, being loaded and unloaded with the same stiffness, and thus

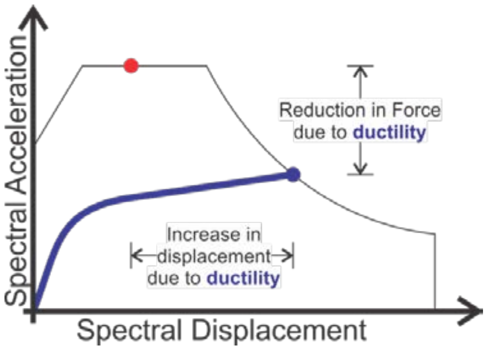

Figure 4. The structural capacity curve of an ductile SDOF without hysteretic properties.

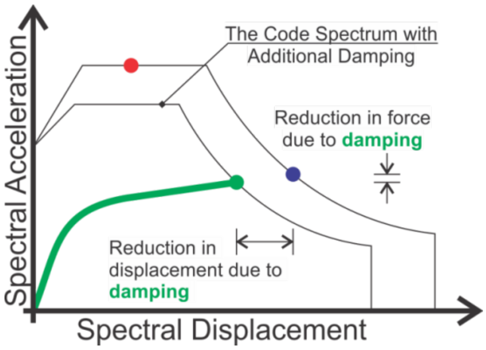

Figure 5. The structural capacity curve of an in-elastic (i.e. ductile) SDOF with hysteretic properties.

the same period. For most low and medium rise structures the performance point of the structure will be on the constant acceleration section of the demand spectrum.

Introducing ductility creates a reduction in the stiffness of the building as shown by the curved blue line in Figure 4. This change in stiffness elongates the period. This period shift creates a significant change in the performance point of the structure. The force experienced by the structure is reduced but as a consequence displacements increase well beyond what would be expected under elastic response.

The spectrum shown in Figure 4 has not been altered from the elastic spectrum and maintains the damping ratio of 5%. This alteration of the performance point is thus only attributable to the period shift created by the change in stiffness.

The addition of hysteretic damping is represented on the ADRS as the reduction of the demand with increasing hysteretic damping shown by the inner curve in Figure 5. This creates a new performance point for the damped system, as shown.

Introducing hysteretic damping reduces demand creating a reduction in displacement. Figure 5 shows however that there is only a minor decrease in force due to damping beyond that already created by the period shift. In order to dissipate hysteretic energy the system by definition must be beyond its initial elastic range which is normally of nominal stiffness. Thus, minor modifications in damping impact the displacement significantly more than they impact the force. Iteration is normally required to find the performance point of a hysteretic system because a reduction in final displacement will lower the hysteretic energy release from the system.

4 RELEVANCE TO TIMBER BUILDINGS:

Timber buildings have some structural advantages (e.g. low mass) and some major environmental advantages (e.g. renewable resource, low carbon footprint), and they are generally equivalent to steel and concrete with regard to construction time and cost. However, the lower Modulus of Elasticity of wood compared with concrete or steel can result in larger elastic displacements of timber buildings in most loading conditions, hence a smaller "displacement window".

A small displacement window may be a particular problem for some timber building types, especially those with moment-frames or slender walls, because the elastic displacements will be larger than for similar concrete or steel buildings. For example, in a reinforced concrete building, if yielding occurs at 0.5% drift with a design limit of 2.5% drift, there is a displacement window of 2% drift for ductility and energy dissipation. In comparison for a very flexible timber building, if yielding does not occur until 2% drift, the displacement window has been drastically cut to only 0.5% drift.

This issue becomes crucially important for the new generation of damage-limiting timber structures where hysteretic damping is concentrated in yielding steel devices and period shift is created by gap opening. The smaller the displacement window, the more difficult it becomes to design for a significant level of structural ductility and damping.

5 SOLUTIONS

There are several possible solutions to the problem caused by the small displacement window in multi-storey timber buildings.

- Use stiffer materials
- Change the geometry to design a stiffer structure
- Concentrating the inelastic behaviour at specific points

This section discusses the way in which these approaches can be used to increase the displacement window and presents case study structures in which the techniques have been successfully used.

5.1 Stiffer materials

The stiffness of a structure is mainly related to EI, through material properties and structural geometry respectively. Hence the two ways to design a stiffer structure are to increase one or both of these.

The modulus of elasticity of wood can vary widely depending on species, but commercial softwoods available in New Zealand and Australia are in a narrower band. An advantage of engineered wood products such as laminated veneer lumber (LVL) is that its mechanical properties are accurately defined. All manufacturers in New Zealand can produce LVL with E=11GPa, with some able to produce E=13GPa and even E=16GPa in smaller quantities, while LVL with E=17GPa is standard production for one Australian manufacturer.

Two examples where stiffness has been increased creating an increase in the displacement window are the new office structure for Trimble Navigation Ltd. and Wynn Williams House. The new offices for Trimble Navigation, shown in Figure 6, combined the use of Pres-Lam frames and walls and specified high stiffness HyONE LVL. This reduced column and joint panel deformation ensuring both yield and ductility under more stringent than code (1.65% drift) displacement limits. (Brown et al. 2014). The designers of Wynn Williams House increased the stiffness of the columns by using pre-cast concrete. Although this was done to manage increased stresses from the bidirectional application of post-tensioning, it can be considered as another valid method of increasing the displacement window.

Office building for Trimble Navigation, Christchurch, increased stiffness of the columns by specifying stiffer timber material.

Wynn Williams House, Christchurch, increased stiffness of the columns by specifying reinforced concrete.

Figure 6. Buildings where the displacement window is increased with stiffer materials.

5.2 Stiffer geometry

The other main way to increase the structural stiffness is to change the geometry, by increasing the size of structural elements, adding walls in line with structural frames to create a dual system, stitching walls together in order to change their structural form (i.e. I-section and C-section structural walls around lift shafts).

The increased stiffness and displacement window of structural walls has led to their use being the most common form of timber construction both historically and today. Where many walls are available, a designer is able to create a stiff structure with the use of Cross-Laminated Timber (CLT) or Light Timber Frame (LTF). Both of these structural forms rely on the high stiffness created by the geometry of the wall panel to displace and yield fasteners creating both ductility and damping. Where larger open spaces are required, Pres-Lam walls can be used which use stiff monolithic panels to concentrate the displacement at the base of the structure. The Arts & Media Building of the Nelson Marlborough Institute of Technology (NMIT) (Devereux et al. 2011) and the Carterton Events Centre (Palermo et al. 2012) both resist lateral loading through the use of deep, high section modulus, Pres-Lam walls, as shown in Figure 7.

Arts and Media Building, Nelson, increased stiffness through increased section modulus.

Carterton Events Center, Carterton, increased stiffness through increased section modulus.

Figure 7. Buildings where the displacement window is increased with increased section modulus.

5.3 Concentrating the inelastic behaviour at specific points

The displacement window is used to provide ductility and damping to a structure which lowers displacement and force during a seismic event. Traditionally in timber this ductility and damping has been beam-column, column-foundation or wall-foundation connections of concentrated at the connections around and between panels. It is possible however to increase the displacement window by concentrating this inelastic behaviour at other points within a structure such as cross bracing or base isolation.

Two buildings which have done this are Wynn Williams House and the College of Creative Arts at Massey University, as shown in Figure 8. In addition to the concrete columns, Wynn Williams House is base isolated between its basement level and ground floor. The use of base isolation significantly alters the response of a structure by effectively concentrating displacement at the base isolation level. The displacement window in a base isolation system is limited by the base isolation device and its ability to move, not building performance. Most base isolation systems also provide damping.

By placing dissipative devices on the top of concrete walls attached to the underside of the first floor beams, the College of Creative Arts at Massey University used the full inter storey drift as its displacement window. The designers recognised that this inter storey displacement was much larger than the local displacements at the beam-column joints, so it was structurally more efficient to concentrate the dissipative devices at this location. Combining the dissipative devices with an elastically responding system reduces the amount of period shift in the structure, however careful positioning of the devices can activate them earlier and hence increase damping significantly.

Wynn Williams House, Christchurch, Alteration of the treatment of the displacement window through base isolation.

CoCA building, Massey University, Wellington, Concentration of dissipative devices at first floor level.

Figure 8. Buildings where the displacement window is increased with concentrated inelastic behaviour.

6 FURTHER CONSIDERATIONS FOR THE DISPLACEMENT WINDOW

In the section above three methods have been described which enable a designer to increase the displacement window of a timber structure. Several further considerations regarding the use of this displacement window are discussed in this section.

6.1 Connection stiffness

Increasingly in timber structures, damping energy tends to be designed into discrete steel connections, often taking the form of replaceable yielding devices, rather than being buried in the main structure. With a small displacement window, the replaceable devices will never be activated if they are too flexible or have sloppy connections, so very careful design and detailing is necessary to ensure that flexible connections do not eat even further into a tight displacement window.

Testing at the University of Canterbury has shown that timber rivets can provide very stiff and strong shear connections between external steel plates and large timber members, considerably stiffer than nailed or bolted connections (Fig. 9a). If the appearance of riveted steel plates is a problem, they can be placed in internal pockets (as shown in Fig. 9b) but this can add to the time and cost of construction. Epoxied steel rods and bearing plates can also be used to give stiff connections (Fig. 9c).

(a) Beam-column connection using rivets.

(b) Column-foundation connection with rivets hidden in a cut-out recess.

(c) Detail of exposed yielding devices with epoxied connection into the post-tensioned beam.

Figure 9. Examples of the connection of dissipative elements.

This point is especially critical in the design of dissipative cross bracing in timber buildings. The connections of the timber members and the members themselves must be treated as a series of springs which need to be designed with sufficient stiffness. The connections of these elements will often need to be designed for stiffness in addition to strength.

6.2 **Local reinforcement to increase stiffness**

It is possible to limit elastic deflections through the local reinforcement of timber members thus increasing the displacement window. This can be done through the addition of stiffer materials into the beam, column or wall members.

One common method used to increase the displacement window in frames is to add steel plates at the beam-column joint. In order for this to be effective however the steel plate must become fully composite with the joint which requires careful study of the stiffness of the connections. With wall systems it is possible to add stiffer materials to the edges of the section increasing the stiffness, a common practise in the manufacture of glue laminated timber. Careful attention must be paid however to the stresses created in glue lines between the two materials. Details with long threaded screws are often more effective.

7 **CONCLUSIONS:**

The main conclusions from this paper are that:

- Displacements often govern the design of timber structures.
- Design to control displacements is becoming increasingly important in seismic design, to reduce the potential costs of structural and non-structural damage.
- Multi-storey timber buildings can achieve the same level of performance as concrete or steel buildings, with careful design and attention to detailing.
- Ductile design is only possible if there is a sufficiently large displacement window between onset of yield and the ultimate displacement limit.
- The displacement window can be increased by using higher stiffness materials and geometries, or by changing the way in which the displacement window is used within the building.
- These issues apply to building designs using all materials, but are especially important for low modulus materials such as timber.

8 **ACKNOWLEDGEMENTS**

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