Design of floor diaphragms in multi-storey timber buildings

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ABSTRACT: This paper discusses the design of timber diaphragms, in response to the growing interest in multi-storey commercial timber structures, and the lack of guidance or regulations regarding the seismic design of timber diaphragms.

Proper performance of floor diaphragms is required to transfer all lateral loads to the vertical systems that resist them, but design for earthquake loads can be more complex than design for wind loads. This paper confirms that the seismic design of a diaphragm is intimately linked to the seismic design of the whole building. Diaphragm failure, even if restricted to a limited diaphragm portion, can compromise the behaviour of the whole building. It is therefore necessary to design and detail diaphragms for all possible load paths and to evaluate their influence on the load distribution within the rest of the structure. It is strongly recommended that timber diaphragms be designed as elastic elements, by applying dynamic amplification and overstrength factors derived from the lateral load resisting system.

This paper shows that some current design recommendations for plywood sheathing on light timber framing can be applied to massive wood diaphragms, but for more complex floor geometries an equivalent truss method is suggested. Diaphragm flexibility and displacement incompatibilities between the floor diaphragms and the lateral resisting systems also need to be accounted for.

1 INTRODUCTION

Recent years have seen a growing interest in engineered multi-storey timber buildings around the world. A number of tall timber buildings have been built in Europe, followed by a 10 storey building in Melbourne (Binational Softwood Lumber Council et al. 2014). Both Canada and the US have set up design competitions in order to promote timber as the construction material for tall buildings. The New Zealand construction sector is part of this trend, with a number of commercial timber buildings already built (Ministry for Primary Industries 2014) or in the design process. The local availability of glued laminated timber (glulam), Cross Laminated Timber (CLT), Laminated Veneer Lumber (LVL) as well as prefabricated Light Timber Frame (LTF) elements and the soon to be released new NZ Timber Structures Standard are all encouraging the use of timber for new multi-residential, commercial and industrial buildings.

This new global interest in medium to high-rise multi-storey timber buildings creates the need for a more rigorous approach in design. Furthermore, the presence of some of these structures in seismically active countries has highlighted knowledge gaps regarding their performance under earthquake loading and especially in the design of diaphragms.

1.1 Role of diaphragms

Independently of the construction material used, diaphragms have a multiple role in the structural behaviour of a building. Aside from acting as slabs under gravity loads, diaphragms tie all other structural elements together and transfer horizontal loads to the vertical Lateral Load Resisting System (LLRS). Being the first element to resist most gravity and horizontal forces, a loss of diaphragm action will likely compromise the behaviour of the whole structure.

Recent decades have seen new research regarding the behaviour of diaphragms and their influence on the response of the whole building in case of dynamic loading. This was mainly driven by damage caused to a number of concrete buildings in recent earthquakes, mostly attributed to a lack of understanding of diaphragm functionality and poor design. It has been shown that flexible diaphragms can change the global dynamic behaviour of buildings (Fleischman et al. 2002; Lee et al. 2007), that floor accelerations are often underestimated with traditional design methods (Nakaki 2000; Rodriguez et al. 2002; Bull 2004) and that displacement incompatibilities between the floor diaphragm and the LLRS can compromise load paths (fib 2003; Bull 2004; Fenwick et al. 2010).

Although this paper focuses on seismic design, similar principles regarding force distribution and connection detailing apply to the design of diaphragms for wind loads or other lateral loads on buildings. All forces created within the diaphragm or deriving from load applications along the diaphragm edges need to be transferred to the LLRS. Concentrated forces, floor openings or re-entrant corners create stress concentrations, which need to be accounted for to prevent premature failures. All components of floor diaphragms (chord beams, collectors and strut beams, panel elements and the various connections) need to resist the anticipated forces guaranteeing a clearly defined load path through the structure from the points of load application to the foundations. Under seismic forces, dissipation and ductility should be provided by the vertical LLRS, leaving the diaphragms to work as a whole in the elastic range.

1.2 Seismic design philosophy in current timber codes and guidelines

Compared to concrete or steel structures, there is limited world-wide knowledge on the seismic behaviour of timber buildings. This could be attributed to the fact that most timber research and built examples of timber structures can be found in countries with low seismic risk. Current international codes and standards regarding the seismic design of timber buildings are based on LTF construction (Moroder et al. 2014c). The non-inclusion of new timber engineered products like CLT or innovative building systems like post-tensioned walls and moment resisting frames also hinders a wider adoption of timber for mid and high-rise timber structures. Definitions for ductility, overstrength and dynamic amplification factors are either missing or differ greatly, leaving their interpretation and choice to engineering judgement.

The second generation of Eurocode EN 1998 (European Committee for Standardization 2004) to be published by 2018, some existing North American codes like the SDPWS-2008 (AF&PA American Wood Council 2008), the IBC 2012 (International Code Council 2011), the NBCC 2010 (Canadian Commission of Building and Fire Codes 2010) and the O86-09 (Standards Council of Canada 2009) and the upcoming new version of NZS 3603 (Standards New Zealand 1993) all aim to provide better guidance for the design of multi-storey timber buildings under seismic loading.

2 DIAPHRAGM DESIGN

2.1 Loads on timber diaphragms

All components of floor diaphragms (chords and collector/strut beams, panel elements, panel connections and the connections to the LLRS) must be designed to resist all anticipated loads, including wind loads, seismic inertial loads and any transfer forces.

Seismic loads can be considered as area loads applied to the whole diaphragm surface. Wind loads are normally idealized as uniformly distributed line loads applied to the diaphragm edges. In order to activate the diaphragm, these forces need to be transferred from the façade fixings into the diaphragm plate. This may be achieved via axial forces in the framing elements for LTF diaphragms or directly via longitudinal stresses in massive timber panels. Panel fasteners need to be designed for these additional forces acting perpendicular to the panel edges.

Although it is known (Fleischman et al. 2002; Rodriguez et al. 2002; Bull 2004) that current simplified code methods to evaluate seismic forces underestimate diaphragm forces, only limited guidance is provided in the literature. The forthcoming amendment to NZS 1170.5 (Standards New Zealand 2004) suggests the Pseudo Equivalent Static Analysis (pESA) to determine diaphragm forces (Bull 2004). This method however has only been tested in concrete structures and the applicability to timber structures still needs to be verified. Higher mode effects and the overstrength of the vertical LLRS need to be considered in order to guarantee the diaphragm behaviour throughout an earthquake attack.

Transfer forces can be generated by changes in the LLRS along the height of the building, or by interaction between different types of LLRS (i.e. combinations of wall, frame and core-wall systems), amplified by the large inelastic deformation of the LLRS in case of high ductility demand. Because of the flexibility of timber diaphragms, transfer forces are considered to be less than in typical concrete diaphragms; research on this topic is currently being carried out at the University of Canterbury.

Additional diaphragm loads can also be created by the arbitrary nature of the direction of earthquake attack. While common practice is to separately design orthogonal LLRS (in case of regular building configuration), the lateral movement of the structure in a principal direction may also create out-of-plane movement of any orthogonal LLRS, which must be allowed for in the design.

Figure 1. Light timber frame and massive timber diaphragm examples, with schematic cross sections.

2.2 Elastic versus plastic diaphragm design

Since inelastic deformations in a diaphragm can compromise not only the diaphragm performance but also all other structural elements attached to it, it is recommended that the new NZS 3603, currently under revision, should require elastic diaphragm design as already required by NZS 1170.5. Overstrength values for different types of LLRS and connections also need to be provided.

In spite of this proposed requirement for elastic design, the diaphragm as a whole should have sufficient ductility and ultimate deformation capacity to adhere to the basic requirement of collapse prevention under higher-than-expected seismic loading, either through non-linear behaviour of the connections to the LLRS or between panels. Similarly, when special buildings of high importance level are designed for a ‘maximum considered earthquake’ (MCE, 2500 years return period), some diaphragm yielding can be allowed, with designated ductile connections and prevention of brittle failures. Special analysis needs to be carried out if large portions of diaphragms are ever required to work in the inelastic range.

2.3 New developments in timber diaphragm systems

Traditionally, timber diaphragms consist of wooden sheathing on light timber framing (see Fig. 1). This construction type has been used for floors and for large panelised roof systems for industrial buildings. Recent innovations however have opened the possibility of using larger massive timber panels made of LVL, CLT or glulam, as well as pre-assembled Structural Insulated Panels (SIPs), allowing the design of large floor geometries in a cost-effective manner.

Diaphragms built from massive timber panels have not yet been codified and recent research on CLT structures is often limited by assuming diaphragms as being rigid. This is normally justified by the limited size of residential floor geometries and by using sufficient overstrength for the diaphragm design (Ceccotti 2008; Dujic et al. 2010; Follesa et al. 2013). Regardless of a flexible or rigid floor diaphragm assumption, the forces in the panels, beams and connections need to be verified. The increasing use of these massive timber systems for multi-residential and commercial buildings with larger floor spans and multiple rows of panels will require the calculation of deformations in order to verify the rigid diaphragm assumption and the resulting force distribution.

2.4 Massive timber diaphragm design

Design approaches with the 'deep beam analogy' (Countryman 1952; ATC 1981; Smith et al. 1986; Prion 2003) with its improvements found in the 'shear field analogy' (Kessel et al. 2001; Blaß et al. 2004) and the use of transfer diaphragms (Malone et al. 2012) have led to satisfactory designs for LTF diaphragms, but little is known about the behaviour of massive timber diaphragms.

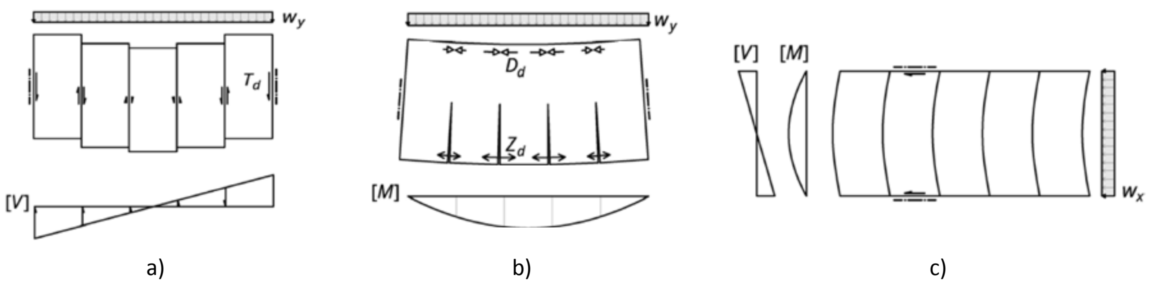

Figure 2. Failure mechanism of floor diaphragms: a) shear along panel connection, b) chord forces, c) diaphragms as series of beams (Wallner-Novak et al. 2013).

Wallner-Novak et al. (2013) discuss the design of floor diaphragms made from CLT panels and refer also to the deep beam analogy as shown in Figure 2 (a and b). The panels and panel connections which resist the shear and tension/compression forces along the edges are taken by chord beams or are transferred by appropriate connectors. For loading perpendicular to the panel length (Fig. 2c), the diaphragm can be assumed to work as a series of beams in parallel.

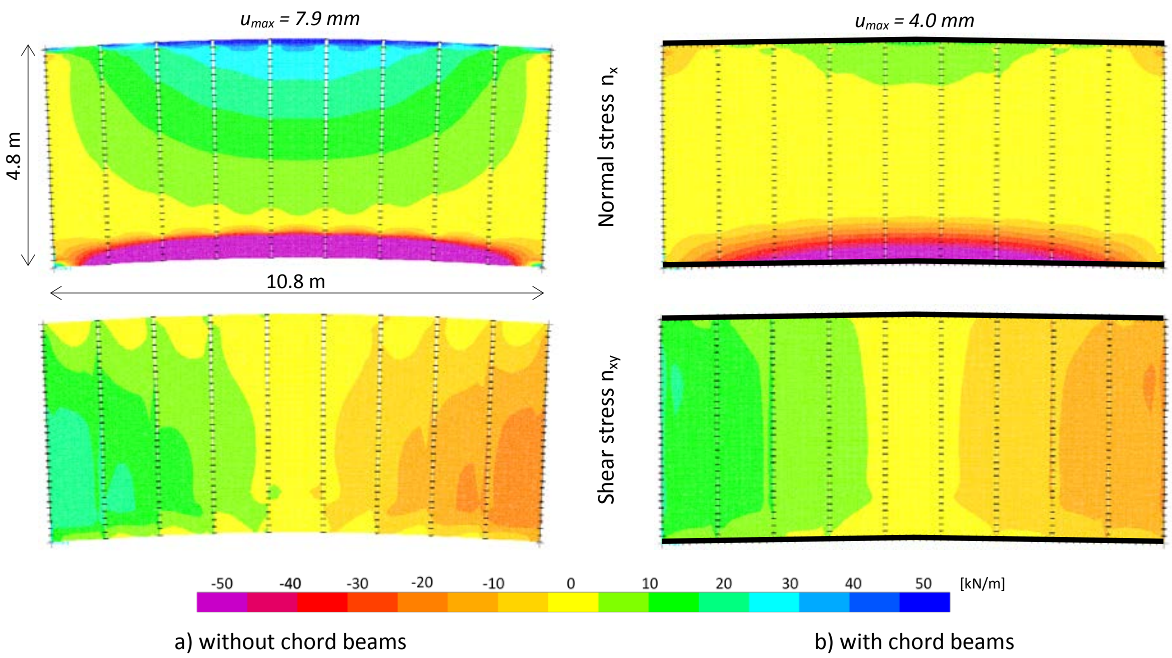

Figure 3. Simply supported diaphragms a) without and b) with chord beams.

To verify the deep beam analogy for massive timber diaphragms, a simple FEM analysis was carried out in SAP2000 (CSI Computers and Structures Inc. 2004). CLT panels of 1.2 x 4.8 m were modelled as orthotropic membrane elements (E_1 = 8 GPa, E_2 = 4 GPa, E_3 = 0.5 GPa, G_{12} = 600 MPa, G_{13} = 500 MPa, G_{23} = 100 MPa, υ_{12} = 0.07, υ_{13} = υ_{23} = 0.35) (Ashtari 2009) and the panel connections made of Ø6 mm screws at 150 mm on a lap joint, were modelled with linear elastic link elements (slip modulus K_{ser} = 3000 N/mm parallel and perpendicular to the panel edge). A seismic force of 3.5 kN/m^2 was applied as a surface load. Figure 3 shows the stress distributions for a simply supported diaphragm with and without chord beams. The contours show normal stresses (tension/compression stresses parallel to the span) and shear stresses in the panels.

2.5 Equivalent truss method (strut-and-tie for timber)

Even though these studies confirmed the eligibility of the deep beam analogy for massive timber diaphragms, complex floor layouts require an alternative approach. For geometries with a limited number of irregularities, transfer diaphragms (sub-diaphragms) (Malone et al. 2012; STIC 2013) can be adopted, leaving more complex diaphragms to be modelled with a finite element analysis.

With the increasing popularity of strut-and-tie analysis (Schlaich et al. 1988) for concrete diaphragms (Bull 2004; Moehle et al. 2010) the authors encourage the adoption of an equivalent truss method for the analysis of complex timber diaphragms, as has also been proposed for concrete diaphragms (Bull et al. 2014; Scarry 2014). Initially proposed by Hrennikoff (1941) for generic elastic materials, Kamiya (1990) applied the truss method to analyse timber diaphragms with openings. Kessel et al. (2001) derived the equivalent diagonal stiffness for LTF diaphragms based on the ‘shear field analogy’ (see Figure 4). This concept has been further refined and modified by the authors for use with LTF and massive timber diaphragms. Because strut-and-tie models rely on the tensile strength of reinforcement bars and the compression capacity of the concrete, the arrangement of the strut and ties is not unique. For timber diaphragms the size of the panels is well known and each panel is delimited by the fasteners with their relative stiffness. The equivalent diagonals therefore can be placed across each panel element; in the case of overly acute angles or diaphragm irregularities, multiple diagonals can be used to model one panel element. Since the panel connections are the main source of diaphragm flexibility, they need to be accounted for in the diagonal stiffness. Even though some assumptions required by the shear field analogy are not satisfied for massive timber diaphragms (i.e. the sheathing panels are surrounded by framing elements, the longitudinal stiffness of the panels is negligible compared to the axial stiffness of the framing members etc.), the panels mainly work in shear, with longitudinal stresses induced by local irregularities or discrete forces.

Once the equivalent shear-through-thickness rigidity of the panel $(Gd)_{ef}$ including the fastener stiffness $K_{ser\,||}$ parallel to the edge is evaluated for massive timber panels

$$(Gd)_{ef} = \left[\frac{1}{Gd} + \frac{s}{K_{ser\,||}}\left(\frac{1}{b} + \frac{2}{h}\right)\right]^{-1}; \tag{1}$$

the equivalent diagonal stiffness E_{ef} can be determined by assuming the diagonal’s cross section equal to its length $A_{ef} = l$:

$$E_{ef} = \frac{(Gd)_{ef} l^2}{hb}; \tag{2}$$

where:

	G…	shear modulus of the sheathing;
	d…	sheathing panel thickness;
	$(Gd)_{ef}$…	equivalent shear-through-thickness rigidity of the panel;
	E_{ef}…	equivalent modulus of elasticity of the diagonal;
	A_{ef}…	equivalent cross sectional area of the diagonal;
	$K_{ser\,||}$…	slip modulus of the fastener parallel to the panel edge;
	s…	fastener spacing;
	b…	panel width;
	h…	panel height;
	l…	diagonal length = $\sqrt{h^2 + b^2}$.

By setting the equivalent diagonal cross sectional area A_{ef} equal to the diagonal length, the unit shear force in the panel (that is the shear force per length) can be obtained as the normal stress in the diagonal. To obtain the tension/compression forces in the chord and collector beams, the sum of unit shear forces along the element length needs to be included. This is because the diagonal introduces the equivalent panel force in the nodes, whereas in reality it is introduced gradually through the fasteners along the panel edge.

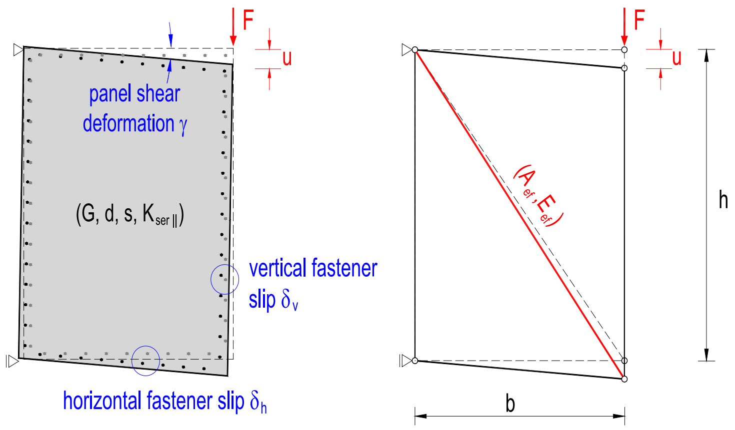

Figure 4. Shear panel with fastener stiffness and equivalent truss diagonal.

Because massive timber panels possess relatively high axial stiffness compared to LTF panels, normal stresses n_{xx} and n_{yy} along the two main directions need to be accounted for. Additionally, fasteners will not only transfer forces parallel to the panel edges, but also perpendicular to them. By dividing the panels into multiple diagonals as shown in Figure 5, the horizontal truss elements can account for these effects by including the fastener stiffness perpendicular to the panel edges.

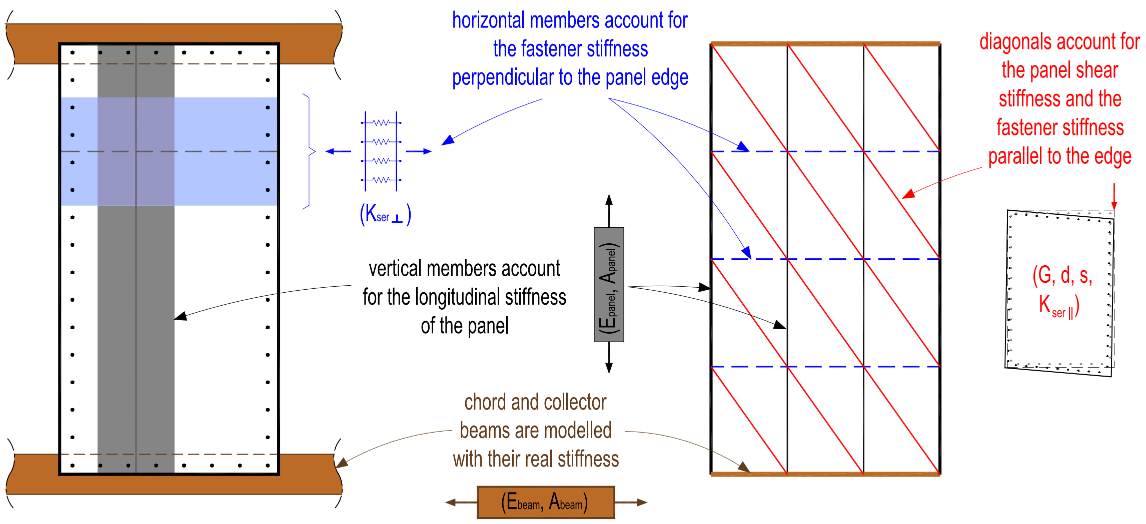

Figure 5. Massive diaphragm panel and its idealization in the equivalent truss model in the case of multiple diagonals.

Figure 6 shows the FEM analysis and equivalent truss method for an irregular floor layout made of 1.05 x 3.9 m CLT panels, with loads applied in the direction up the page. Panel and connection properties and loading assumptions are the same as for the model shown in Figure 3.

Each diaphragm panel has been modelled with 8 equivalent diagonals. Chord, strut and collector beams have been modelled with their real sections. Loads have been applied as line loads to the truss elements parallel to the loading direction. A comparison of Figure 6a and c show that the unit shear forces can be predicted accurately with the equivalent truss. Also the diaphragm flexibility can be obtained in a very precise fashion as well as the reaction forces (not shown). Figure 6b and d show the compression and tension forces in chord and collector beams from the FEM and the equivalent truss analysis, respectively. Once the tension and compression forces are obtained, the assumed section of the chords and collectors can be verified and their connections or splices can be designed. Knowing the unit shear, the fastener capacity, the panel shear capacity and the buckling strength (the latter two seldom govern the design of massive timber diaphragms) can be verified.

This comparison between a sophisticated finite element analysis and a rather simple truss method for a massive timber diaphragm shows that the latter can predict all key aspects for a diaphragm design in a sufficiently accurate manner. This procedure is even more accurate for LTF diaphragms, since the sheathing panels almost exclusively work in shear. Independently from the type of diaphragm panels adopted, the equivalent diagonal stiffness needs to be calculated, taking into account panel shear stiffness and fastener stiffness.

The proposed equivalent truss method assumes linear elastic behaviour of the fasteners; stress redistributions due to localized fastener yielding cannot be accounted for. Similar to a FEM analysis, the size of the panel subdivision into equivalent diagonals must be chosen carefully. It might be necessary to refine the number of diagonals around areas with potential stress concentrations. Unlike strut-and-tie applications on concrete diaphragms, the diagonal stiffness must be re-calculated and re-assigned if the timber panel subdivision is changed, or the fastener spacing or type is altered.

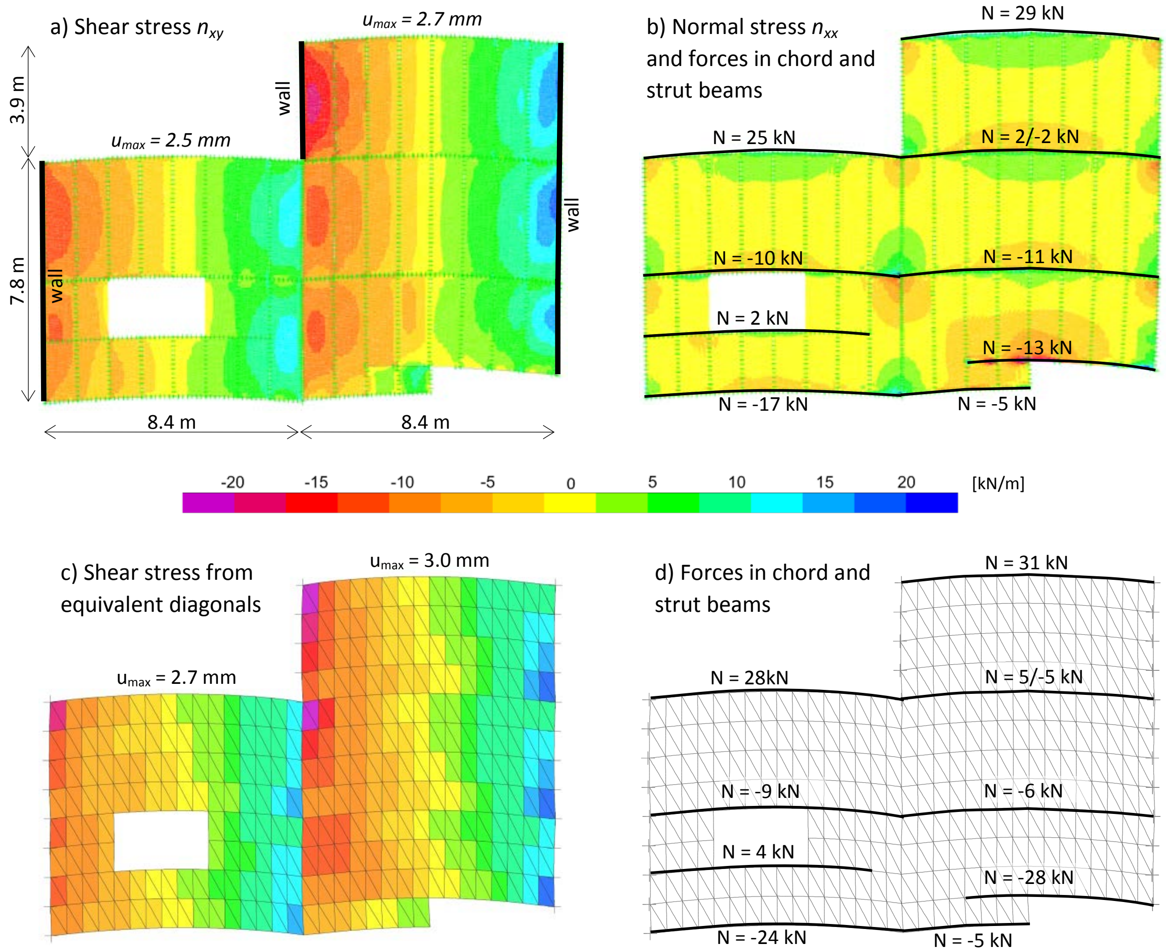

Figure 6. Stress distributions of an irregular diaphragm with chord and collector beams with a re-entrant corner and an opening; a) n_{xy} shear stresses (FEM); b) n_{xx} normal stresses and forces in chord and strut beams (FEM), c) shear stresses (equivalent truss) and d) forces in chord and strut beams (equivalent truss).

2.6 Rigid versus flexible diaphragm design

Depending on the relative stiffness between the diaphragm and the LLRS, horizontal forces are distributed to the LLRS according to tributary areas in the case of flexible diaphragms or according to the relative stiffness of the LLRS elements in the case of rigid diaphragms. Rigid diaphragms also require the analysis of torsional effects.

To define whether the diaphragm is rigid or flexible, the deflection calculation for both the vertical LLRS and the diaphragm is required. In the case of a simply supported LTF diaphragm a commentary clause in NZS 3603 (Standards New Zealand 1993) provides a simple equation to calculate the deflection. The total deflection is made up by the flexural deflection related to the chord beams, the shear deformation of the sheathing panels and the fasteners' slip.

Based on first principles, this equation has been modified in order to predict deflections of massive timber diaphragms, giving:

$$u = \frac{5WL^3}{192EAH^2} + \frac{WL}{8GHd} + e_n(1 + 2\,\alpha)\frac{m}{4}; \tag{3}$$

where:
- W… lateral load applied to the diaphragm[1];
- L… span of the diaphragm;
- E… elastic modulus of the chord members;
- A… cross sectional area of one chord [mm^2];
- H… distance between chord members (diaphragm height);
- d… sheathing panel thickness;
- G… shear modulus of the sheathing;
- m… number of sheathing panels along the length of the chord member;
- α… sheathing panel aspect ratio $\alpha = b/h$;
- e_n… fastener slip of the panel-to-panel connection.

The first two terms are equivalent for both LTF and massive timber diaphragms. The fastener slip term has been modified to account for the fact that the unit shear force is transferred from one panel directly to the adjacent one. The fastener slip e_n is calculated for the maximum unit shear force at the support. Since all diaphragms should be designed as elastic, the slip only depends on the slip modulus and spacing of the fasteners. Equation (3) can be modified when different fasteners are used for the panel-to-panel, panel-to-chord and panel-to-collector connections.

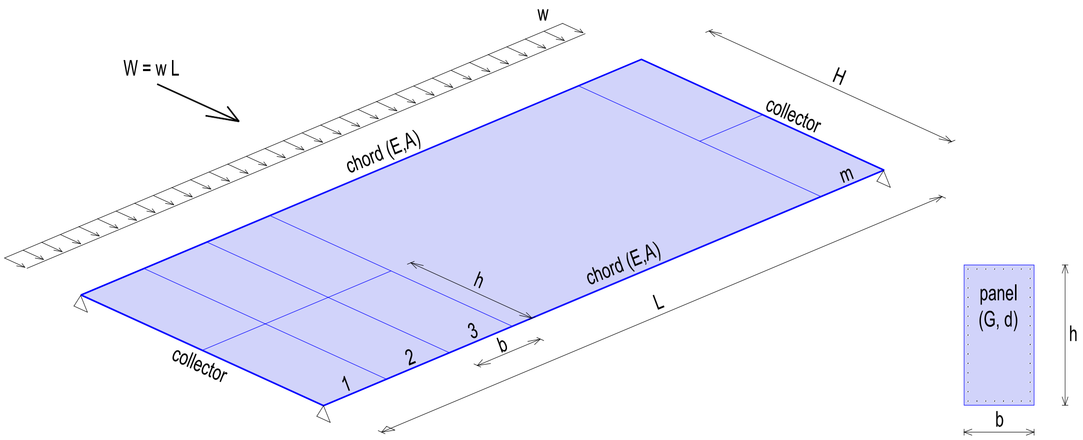

Figure 7. Diaphragm notation.

The deflection equation provided in NZS 3603 and Equation (3) are only applicable to simply supported blocked diaphragms with chord beams. To account for diaphragm irregularities such as variable loads, openings, re-entrant corners, changes in diaphragm depth or staggered fastener layouts, these equations can be integrated over parts of the diaphragm (Malone et al. 2012). This procedure however is not always readily applicable and therefore seldom used in design offices.

For irregular diaphragms the authors suggest the use of the equivalent truss method to determine deflections. Deflections calculated by a finite element analysis compare relatively well with the outcome from the truss method as shown in Figure 6.

Since the vertical LLRS can also be easily modelled (via flexible supports or by vertical equivalent trusses), the global building behaviour can be analysed accounting for all involved stiffnesses, achieving automatically the correct force distribution in the diaphragm and the LLRS.

[1] The lateral load is assumed as a uniformly distributed load, the current code equation however requires the resultant load $W = w\,L$

2.7 **Displacement incompatibilities**

Careful design and detailing is essential to avoid damage from displacement incompatibilities within diaphragms or between diaphragms and the LLRS. This problem, which is normally associated to concrete and steel structures (fib 2003; Bull 2004; Eatherton 2010; Henry et al. 2012; Latham et al. 2013) can also be seen in traditional and innovative timber structures (Hummel et al. 2012; Moroder et al. 2013; Wrzesniak et al. 2013; Dunbar et al. 2014; Loo et al. 2014; Moroder et al. 2014a; Sustersic et al. 2014).

Beam elongation in frame structures and uplift and rotation of walls need to be considered when detailing floor diaphragms and their connections, to guarantee the predicted behaviour of the structure under seismic actions. Experimental testing has shown that the flexibilities of timber members and steel fasteners can, in many cases, accommodate the required displacements without compromising the diaphragm behaviour (Moroder et al. 2014b).

3 **CONCLUSIONS**

The following conclusions can be drawn from the review of literature, code design provisions and research carried out by the authors:

General principles

- Diaphragms have an essential role in the lateral load resistance of buildings and special care should be taken in their design.
- All diaphragms should be designed to remain elastic under seismic loading, by applying an overstrength factor from the LLRS to the diaphragm demand as a whole. All designs should provide ductile behaviour for higher-than-expected forces or displacements under extreme loading conditions.
- Diaphragm flexibility (including connections to the LLRS) can change the load distribution to the LLRS and the dynamic behaviour of the whole building.

Design of timber diaphragms

- The general design principles for traditional plywood sheathed diaphragms can be applied to massive wood floor diaphragms, only for regular floor geometries.
- Irregular diaphragms often incur stress concentrations and require additional collectors or strut beams to transfer these into less disturbed areas. The equivalent truss method is a valid approach to quantify panel stresses and beam forces for such situations for both LTF and massive timber diaphragms.
- Diaphragm deformations can be evaluated by equations provided in NZS 3603 for LTF diaphragms, or by the proposed equation for massive timber diaphragms. For irregular floor geometries the truss methods can be used to evaluate diaphragm deflections.
- Dynamic amplification from higher mode effects needs to be considered for diaphragms.
- The design and detailing of connections between the diaphragm and the LLRS must take into account any possible displacement incompatibilities.

Future Research needs

- Derivation of dynamic amplification factors for tall timber structures with and without flexible diaphragms.
- Determination of accurate overstrength factors for timber building systems and fasteners.

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