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Differential Movements in a Timber Multi-Storey Hybrid Building

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Abstract

Focus of this paper is likely effects of differential movements due to shrinkage in relatively tall and large (circa 8-storey non-residential) hybrid buildings that combine glued-laminated-timber (glulam) frameworks and cast-in-place reinforced concrete (RC) building cores in their superstructure systems. In such systems RC cores act as stiff lateral load resisting substructures to which a glulam skeleton framework is directly attached. A simplified preliminary three-dimensional finite element analysis of deformations and internal forces created by combined effects of RC and timber shrinkage is presented. Based on that analysis it is concluded that shrinkage, occurring after concrete is cast and timber is placed into position, could have significant impact on the performance of structural components and the entire systems if close attention is not paid to construction details and practices. Effective countermeasures against poor performance focus on correct choice and correct installation of connections within glulam frameworks and between those frameworks and RC building cores. Although some major issues have already been identified the investigation reported here is far from complete and will continue for about 2 more years.

Keywords: buildings, differential movements, hybrid construction, shrinkage, timber.

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1. Introduction

Deformation and movement incompatibilities in hybrid buildings occur when interconnected parts of structural systems distort differently, under influences affecting them in whole or in part. Differential movements most often calculated by engineers are those resulting from differentials in elastic

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compliances of interconnected parts of systems. Here emphasis is on time dependent differential movements that occur due to differential dimensional responses of interconnected parts as the result of differentials in physical responses of materials from which parts are made. The processes of interest in the case of building superstructures manufactured by combining the timber products glued-laminated-timber (glulam) concrete and steel are; aging, curing and creep of concrete and swelling or shrinkage and creep of glulam. The physical processes are highly complex and the temporal variations in magnitudes of resulting strains and deformations in structural systems are strongly related to moisture movements within parts, ambient temperature and moisture exchanges between joined materials and between parts and surrounding air. It follows therefore that design and construction decisions and practices and environmental factors strongly influence differential movements with superstructure systems. Conversely, it is also possible to control and mitigate magnitudes and impacts of differential movements via engineering decisions. This paper discusses initial activities within a Canadian project aimed at identifying the likely extent of differential movements due to shrinkage in relatively tall and large (circa 8-storey non-residential) hybrid buildings that combine glulam frameworks and cast-in-place RC building cores in their superstructure systems, and thence ways of controlling their occurrence and impacts.

Shrinkage in concrete normally occurs due to hydration as cement hardens, temperature differentials between concrete surfaces, moisture adsorption or desorption and the drying process of hardening concrete (Nawy, 1997). Glulam members are made by bonding together relatively thin (usually 19 or 38mm thick) layers/laminations of sawn lumber using rigid synthetic adhesive. Therefore their physical and mechanical characteristics approximate those of sawn timber but are more homogenized because of the laminating process. Like other types of structural timber products, glulam shrinks or swells as moisture is gained or lost by absorption or desorption processes. The largest incremental dimensional change of members in building superstructures is usually shrinkage between the time of installation and attainment of approximately stable dimensions after members have dried from their moisture content at the time of installation (typically around 15%) to interior or protected service moisture content (typically around 6 to 8%). Sealing surfaces of members can retard the rate of moisture exchange between glulam and surrounding air, but a balance is always eventually established between internal conditions of members and their service climates that corresponds to the equilibrium moisture content (EMC) for the service climate. Temperature related dilations of glulam members within buildings normally second order effects and are typically neglected. Seasonal and diurnal fluctuations in service climate tend to have much lesser influences on member dimensions than the initial drying and they also tend to be neglected for indoor service climates. Thus predicting dimensional changes in glulam members, and structural systems containing them, as they dry to attain their characteristic in-service EMC is the issue of most practical concern (Zhou et al, 2000). *<u>Aside:</u> Alterations in the use of any building can have significant effects on EMC values.* For hybrid building superstructures that contain RC and timber members and/or substructures both types of 'material' can be altering dimensions simultaneously due to physical and chemical (in the case of RC) processes during and after construction. Shrinkage distortions of hybrid superstructures depend on many factors but the most important from an engineering perspective are: the nature of the structural arrangement and especially the degree of static indeterminacy, the sequencing of construction processes (e.g. age of RC substructures when the glulam framework is installed), and the service climates to which members and substructures are exposed. For statically determinate superstructures physical processes that cause dilation of their parts will alter the overall dimensions and possibly alter their shapes, but does not induce stresses in the system. *<u>Aside:</u> This does not be confused with lack of intra-part stresses that result from intra-part variability in materials or composite action of steel and concrete in RC.* Dilation of part of statically indeterminate superstructures always causes both distortion and internal stress flows. Both glulam and concrete exhibit creep and therefore stress relaxation occurs as a delayed process that often alleviates stresses built up due to shrinkage or other long-term strains causing processes.

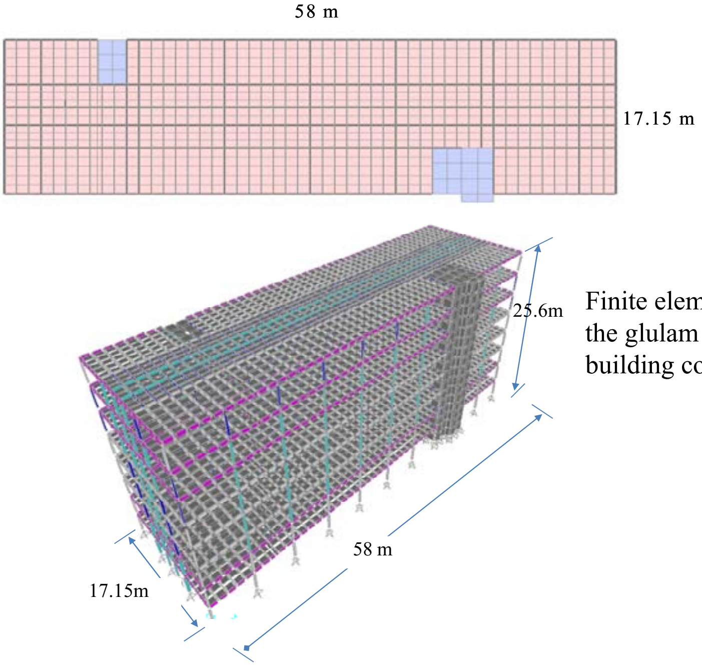
As is normal with properties of timber products, shrinkage coefficients depend on the direction relative to the pith of the tree from which lumber laminations were cut (FPL, 1999). Approximately the shrinkage response can be considered orthotropic and characterised in terms of the responses in longitudinal (parallel to pith), radial (to pith) and tangential (to growth ring) directions (Dias et al, 2007). Shrinkage coefficients depend on the wood species (and the increment of moisture change. For spruce species which are commonly used in Canada for glulam the average tangential shrinkage from green (cell walls saturated) to oven-dry moisture condition is 7 to 8%, the average radial shrinkage is about 4% and longitudinal shrinkage is 0.1 to 0.2% (Schoenmakers, 2010). Shrinkage of normal plain concrete (circa 35MPa compressive strength without reinforcement) is typically isotropic and in the order of 0.03 to 0.04% in any direction from the time of placement to when concrete has hardened (Nawy, 1997). However, the shrinkage of RC is constrained by the presence of steel reinforcement and shrinkage will be much less especially with respect to the in-plane responses of slabs.

In the context of hybrid construction of the type discussed here it is not possible to deduce directly what will be the relative importance of total shrinkage in RC and glulam parts based on unconstrained possible shrinkages of the constituent materials. Indicated levels of RC shrinkage will occur irrespective of other factors if contraction of parts is unconstrained in statically determinate systems, or stresses will be built up if their contraction is constrained in statically indeterminate systems. Even for statically determinate systems it has to be considered what proportion of the possible green to oven dry shrinkage will occur after glulam parts are installed. Because of the nature of construction materials involved it is never actually possible to create fully fixed end conditions on glulam (or other structural timber product) parts of systems and most often connections are semi-rigid (Smith, 1999). Nevertheless in design engineers typically assume either pinned of fully fixed end conditions. It has often been argued that in many instances structural timber connections approximate pinned end conditions but in reality neither situation is realistic (Polastri et al, 2009). For this reason if no other (i.e. construction processes could result in at least partial if not total concrete shrinkage before glulam frameworks are attached to RC frameworks) real glulam-RC hybrid superstructure systems will almost always develop internal stresses due to material shrinkage as time dependent responses to temporal processes.

The remainder of this paper discusses some initial aspects of work in Canada intended to address the likely magnitude and thereby likely importance of differential movements due to shrinkage in relatively tall and large (circa 8-storey non-residential) hybrid buildings that combine glulam frameworks and cast-in-place RC building cores in their superstructure systems. In such systems RC cores act as stiff lateral load resisting substructures to which a glulam skeleton framework is directly attached. Glulam frameworks in such systems are typically not braced in vertical planes but develop some self-sufficient resistance to lateral design loads because of the already mentioned semi-rigid nature of framework connections. However RC building cores, and sometimes discrete RC shear walls, are the primary vertical lateral load resisting elements, with a common design assumption being that they will be required to resist 100% of lateral wind and seismic design forces (Gagnon et al, 2010). Horizontal diaphragms at elevated floor levels and roof level that are attached to glulam frameworks maintain the plan shape at various levels under effects of lateral design forces and also act as collectors for transfer effects of gravitational design loads glulam frameworks that are primary resistive systems for such forces. Glulam frameworks and RC building cores in superstructures are normally attached to relatively rigid RC foundation systems. The structural logic of the systems interacts with material responses to determine specifics of effects of material shrinkage. Below the case study approach is followed to further elucidate discussion.

2. 3-D System Model

Figure 1 shows representative details of an 8-storey superstructure of a hybrid building used here as a case study. The overall footprint at each level is 1015 square meters and the total height of the superstructure is 25.6 meters above a level rigid foundation. The structural principle and actions match what was discussed above. A crucial feature is that RC shear cores containing staircase, elevator and other shafts are sized to resist 100% of lateral wind and seismic design loads for Quebec City in Canada. The chosen location is one where lateral design loads are significant structural considerations by Canadian standards. Another key structural design consideration is that interior framework columns are placed along the walls of the central corridors (visible in the typical plan layout diagram in Figure 1) to mitigate amplitudes of dynamic floor motions induced by building occupants. Details of the design calculations are given in a separate paper (Gagnon et al, 2010).



Plan layout for the first floor (lowest elevated floor)

Finite element model representing the glulam framework and RC building cores

Figure 1. Typical floor layout and three-dimensional finite element model

The following simplifying assumptions were made about how the structural system behaves for the purpose of preliminary analysis of shrinkage induced distortions in the RC cores and glulam framework:

- Neglect of indeterminacies in the glulam framework that result from partial fixities in connections between members of that framework and in connections between that framework and the foundation and RC building cores, i.e. assume all relevant connections are pinned. Note: Parts within RC building cores were modelled as behaving monolithically, and the base was assumed rigidly attached to the building foundation.
- Neglect of the influence of floor and roof diaphragms on the vertical distortion of the structural system, which is only reasonable for preliminary estimation of vertical deformations.

- Neglect of the influence of non-structural vertical elements (e.g. exterior curtain walls, interior infill walls) on the distortion of the structural system, which is only reasonable if those elements have negligible stiffness and/or are not directly attached to the structural system.
- Neglect of the behaviours of steel parts other than reinforcement in RC parts.
- Neglect of variations in service conditions (temperature and relative humidity of surrounding air), which is often reasonable for buildings with curtain exterior walls and uniform types of building occupancy and when the internal building climate does not fluctuate significantly on a seasonal or diurnal basis.
- Neglect of non-linearity in physical and mechanical responses of materials, which is reasonable if the drying of glulam occurs within the envelope of a normally heated building in Canada.
- Neglect of the temporal nature of construction processes and material response processes that control shrinkage and creep in RC and glulam, which may or may not be acceptable for specific situations.
- Neglect of temperature induced dilations in dimensions of parts, which is reasonable for understanding the global response but not necessarily for understanding the behaviour of construction details like connections or interactions of structural and non-structural parts.
- Neglect of foundation settlement.

This list corresponds to the assumptions normally made by structural engineers when estimating the vertical shrinkage to be expected in timber heavy frame structural systems, and is given in full here with annotative notes to emphasise the extensive nature of approximations inherent to them.

The lower diagram in Figure 1 shows a three-dimensional finite element model of the superstructure consisting of RC core, glulam framework and massive timber floor and roof sub-structures. The model implements all the mentioned simplifications and is based on the commercial structural analysis software SAP2000 (CSI, 2008). RC slabs making up building cores and timber slabs making up horizontal diaphragms are modelled using four-node isotropic shell elements, and glulam framework members are modelled using two-node frame elements. All element nodes have six degrees of freedom (three translational and three rotational). No gaps were incorporated between segments of floor and roof diaphragms which were assumed to be rigidly attached to horizontal glulam members. Slab elements in floor and roof diaphragms attached to glulam frame elements but not to RC building core elements. Primary characteristic dimensions of glulam framing and horizontal diaphragm components are given in Table 1. Walls of RC building cores are modelled as 250mm thick. Primary stiffness properties used to derive element stiffness properties are given in Table 2.

Table 1. Glulam and timber slab dimensions (Gagnon et al, 2010)

Type of Component	**Section dimension (mm)**	**Material**
Beams – floor internal	130 x 418	Spruce glulam
Beams – floor perimeter	130 x 380	Spruce glulam
Beams - roof	130 x 418	Spruce glulam
Columns - interior	275 x 266	Spruce glulam
Columns - exterior	130 x 190	Spruce glulam
Floor and roof slabs	250 to 400 thick	Secondary joists and sheathing

Table 2. Material properties (Gagnon et al, 2010)

Structural components	**Material behaviour**	**Mechanical properties**
Glulam – Spruce	Isotropic	E = 13 GPa; $\nu = 0.3$
Horizontal diaphragm	Orthotropic	E1 = 4.5 GPa; E2 = 1.3GPa, $\nu_{12} = 0.25$
Reinforced concrete core	Isotropic	E = 25GPa; $\nu = 0.25$

E = modulus of elasticity, ν = Poisson's ratio, 1 = major axis direction, 2 = minor axis direction

Analysis reported here is predicated on glulam members drying from an initial moisture content of 15% to a final value of 6% resulting in a conservatively estimated longitudinal shrinkage of 0.1% (see Section 1). Walls and other RC slabs in building cores are assumed to shrink negligibly in-plane (because of constraint by reinforcing steel) and to shrink 0.03% through the thickness. Horizontal floor and roof diaphragms were assumed not to shrink because typically construction materials are pre-dried to relatively low moisture contents and are installed under protected conditions. Determination of system deformations followed standard practices implementable in the SAP2000 software (i.e. technical equivalent to calculation of the effects of thermal expansion).

Employing the model described above calculated shrinkage displacements in RC building cores are realistic in the sense that they reflect three-dimensional system constraints imposed by the monolithic nature of those substructures. *Aside: The reciprocal dependence of horizontal displacements on characteristics of the horizontal diaphragm substructures should be noted.* However, in the case of the glulam framework calculated vertical shrinkage displacements (nodal movements) are simply reflections of cumulative vertical shortenings of parts initially aligned vertically relative to appropriate reference points (i.e. foundation attachment points). As will be realized by readers familiar with details of structural analysis this is because connections of the framework were assumed to be pinned. Thus, vertical shrinkage displacements of the framework substructure could have been calculated directly as the product of initial member length x coefficient of shrinkage x incremental moisture change summed across all elements below the level in the structure that is of interest. Ignoring construction details where vertical and horizontal framework members are joined and at the foundation attachment points, the displacement is linearly proportional to the height above the foundation. *Note: Adopting the employed analysis assumptions all points on any floor or the roof other than where the framework is pin connected to a RC building core (i.e. where vertical displacement depends on vertical shrinkage of those cores and not the glulam) will sink by the same amount.* As already indicated this will often not reflect reality. Calculated horizontal displacements in the glulam framework reflect constraints imposed by horizontal diaphragm substructures the horizontal boundary conditions imposed by the requirements of displacement compatibility at attachments to RC building cores. Provided diaphragm substructure properties are accurately represented estimated horizontal shrinkage displacements will be reliable, within the constraint that the temporal nature of various material processes and responses is neglected.

As the three-dimensional system model existed at the time this paper was written it is clearly incomplete as a tool for understanding material shrinkage related effects on the case study building, or as a tool for drawing deductions about parameters relevant to improved design and construction practices. It is a work in progress and will be refined to elucidate each neglected factor in the listed simplifying assumptions.

3. Construction Detail Models

Work is in progress to develop detailed finite element models of the behaviours of hybrid structural parts like glulam members, timber floor and roof diaphragms and structural connections. These models include all appropriate temporally varying factors that affect physical and mechanical responses of such parts, including interactions with surrounding service climates. The intent is that those detailed models will be use to generate effective response parameters as input to models like that discussed in Section 2.

4. Preliminary Results

Figure 2 shows the deformed shape of the case study building and Table 3 shows selected vertical shrinkage displacements at the roof level. The figure shows the deformations of the entire system after applying shrinkage strain. Even though the analysis undertaken was crude it correctly indicates that distortions of the glulam framework and horizontal diaphragms are most significant in bays where the framework is attached to RC building cores at one end. Although it is not discussed in detail in this paper a second analysis assuming rigid glulam framework connections was undertaken. That second analysis indicated that vertical shrinkage displacements are not highly sensitive to framework connection details. However, this should not be construed as meaning the existence of partial fixities between glulam members will have no significant influence on how framework shrinkage can affect effect building performance. Why is because the most serious implications may relate to development of damaging stresses. <u>*Aside:*</u> *In this respect it is important to remember that building performance relates to the combined influences of stresses caused by shrinkage and effects of other factors (e.g. self weight, imposed loads).*

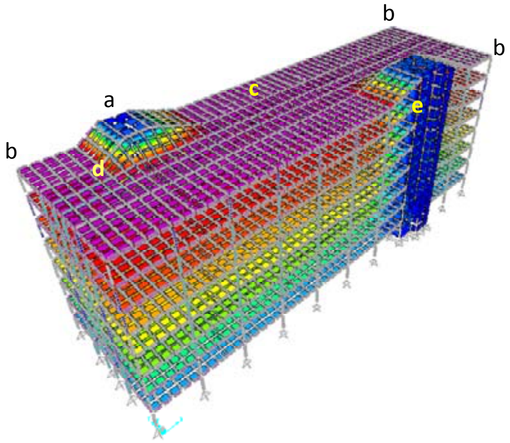


Figure 2. Deformed shape due to differential shrinkage

Table 3. Vertical displacements at roof level

Locations (Figure 3)	Displacement (mm)
(a) Reinforced concrete cores	0.0
All other locations: (b) to (e)	25.6

5. General Discussion

Part of ongoing studies by the authors is definition of design and construction practices that accommodate and minimise the effects of unavoidable deformations associated with differential material responses (incompatibilities) within construction systems of hybrid building that combine structural timber products with product made from non-timber materials.

It is anticipated that numerical models like those discussed here will eventually enable reliable quantitative prediction of how buildings respond to complex situations that occur during their construction and use. Such models will then become tools for establishing best practice recommendations that facilitate decisions by designers (architects and structural engineers) and/or site engineers. The project that supports what is presented in this paper is expected to be concluded in early 2013.

6. Conclusions

The analysis presented here suggests that effects of differential shrinkage in relatively large and tall (circa 8-storey) glulam-reinforced concrete hybrid building are unlikely to be trivial, but can be rendered benign if correct choices are made in respect of construction details and construction practices. Although some key issues have been elucidated further investigation is required.

Acknowledgements

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