CORRIM: Phase II Final Report

Module J

Seismic Code Considerations and Their Life Cycle Impacts of Single-Family Structures

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Prepared by:

Jamie Meil[1]

Mark Lucuik[2]

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[1] Director, Athena Sustainable Materials Institute, Ottawa, On. Canada (corresponding author jamie.meil@athenaSMI.org)

[2] Principal and Professional Engineer, Morrison Hirschfield Consulting Engineers, Ottawa, On. Canada

Executive Summary

This paper describes and considers both the material and life cycle environmental implications of seismic structural designs relative to non-seismic designs in the USA. Using similar wood and steel structural designs for a single-family home modeled in Minneapolis, Seattle and Los Angeles the influence of incrementally greater seismic reinforcement is calculated in terms of embodied primary energy, global warming potential (GWP), air and water pollution and solid waste effects. Results indicate that seismic requirements significantly increase the environmental footprint of residential structures, ranging from an increase of 60 to 100% for energy, GWP and air pollution. The percentage increases from meeting the seismic codes are similar across both wood and steel designs with the increase for a wood design slightly larger than the impact of substituting a steel frame for a wood frame without an increase in seismic requirements. A better understanding of these impacts may motivate design and material use changes as opportunities to lower the environmental impacts in new residential structures.

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Introduction

Much of CORRIM's work to date has focused on alternative material designs for residential single family housing in the continental US (e.g. Minneapolis and Atlanta). Considerable effort went into ensuring that these alternative structural material residential designs (wood, steel and concrete) were functional equivalent and relevant to their regional location. CORRIM wanted to expand the applicability of their research and alternative material design work to other areas of the country – specifically Los Angeles and Seattle, but these two locations are unique relative to the continental United States, in that they are located in areas with relatively high seismic activity and loadings. These seismic loadings in turn result in the use of a number of additional structural materials and systems to satisfy local codes. The purpose of this paper is to describe these additional seismic related structural material requirements, the degree to which they may influence comparable alternative material designs of residential and commercial structures and ultimately, whether these differing seismic requirements, across alterative structural systems, result in significant environmental impact differences from a life cycle perspective. Seismic codes like other building codes are locally controlled and subject to change but the relative magnitudes of the impacts on environmental burdens trace directly from the objectives of the codes to withstand earthquakes with minimal damage.

Approach

Previous alternative design comparisons conducted by CORRIM were completed using the Athena Institute's Impact Estimator software for buildings. The software supports cradle-to-grave life cycle assessment of whole buildings in various regions of N. America. The software incorporates material quantity take-offs for various structural and envelope materials and assemblies and summarizes a building's environmental profile using a set of six life cycle impact assessment measures or indicators. In keeping with the use of the Impact Estimator for buildings software, quantities of materials related to seismic requirements were defined based on either an incremental percentage increase of existing materials, or as a materials list where additional new materials are required. A variety of assembly systems within the Impact Estimator's software were considered for single-family houses, row housing, and low-rise commercial buildings in the two seismic building locations. This paper presents the study's general findings and then concentrates on single-family house seismic requirements and their environmental life cycle implications across two alternative material designs (wood and steel).

Seismic base shear values were calculated to develop seismic requirements across various material assembly types. Seismic base shear calculations for both Seattle and Los Angeles were calculated using the 2003 International Building Code (IBC 2003) and ASCE-7-02 Minimum Design Loads for Buildings as referenced by IBC 2003.

The seismic requirements for lateral load resisting wall systems will vary depending on the height and mass of a building and the structural framing configuration. The requirements will also vary dependent on soil conditions and proximity to active faults. In evaluating the seismic requirements for the wall systems it was necessary to make assumptions as to the soil conditions, proximity to fault lines, and the type of building each wall system will be typically used in.

The additional seismic material requirements for both Seattle and Los Angeles are reported either on a percentage increase basis over non-seismic requirements or as new materials to be added to the assembly as supported by the Institute's Impact Estimator software.

The following is a list of key building type assumptions and criteria used when determining seismic related material requirements for Seattle and Los Angeles:

1) Single-family homes and row housing are considered to be one or two-story wood framed structures.
2) Wood framed wall seismic requirements are based on a typical 3 to 4 story wood framed multi-family residential building.
3) CMU wall seismic requirements are based on a typical single story commercial building.
4) Cast-in-place concrete seismic requirements are based on a four-story building.
5) Tilt-up concrete and pre-cast cellular requirements are based on a two-story building.
6) The additional seismic requirements for all systems are based on an assumption of average soil conditions located no closer than 10 miles to an active fault.
7) Additional seismic requirements assume that none of the buildings being considered are classified as post-disaster buildings.
8) All concrete and CMU walls are considered to be lateral load resisting elements due to the stiffness of these walls.
9) For wood and light gauge steel framed walls, only those walls identified and designed as shear walls are considered to be lateral load resisting elements. The provided material increase is based on an assumption that approximately 50% of load bearing wood framed walls within a wood framed building, regardless of height, will be designed as shear walls.
10) Concrete strip footings are considered to be carrying shear walls. For footings carrying in-fill walls there will be no increase in required materials for seismic requirements.
11) Anchor bolts and tie-down materials for framed walls on concrete footings are assigned to the framed walls.

Applicable Codes Relating to Seismic Design

The following building codes were reviewed and used to determine seismic related design criteria. ***Seattle***: International Building Code (IBC) 2003, International Residential Code (IRC) 2003, ASCE-7-02 ASCE 7-02 (American Society of Civil Engineers) Minimum Design Loads for Buildings and Other Structures,. The Seattle Building Code adopts 2003 Washington State Building Code, which in-turn references IBC and IRC 2003, IBC 2003 references ASCE-7-02).

Los Angeles: Based on IBC and IRC 2003. As of 2007 the State of California adopted the International Building Code over the Uniform Building Code (UBC) 1997. All seismic calculations are based on IBC code requirements. The International Building Code incorporates much of the 1997 UBC requirements but is more refined in the approach to seismic design than 1997 UBC.

Limitations

The seismic requirements reported here are not based on detailed design calculations for any specific building and are intended only to represent changes from a typical design (in a non-seismic zone) that would typically be necessary for a higher seismic zone. It was also assumed that the elements would be applicable only for a typical low-rise structure with average design dead and live gravity load requirements, and assuming reasonably sound soil conditions. Accordingly, the information provided is not applicable to mid-rise or high-rise buildings (five stories or more in height) or buildings with higher than average gravity loading.

There are a number of factors that may impact the actual seismic design of a building and the resulting amount of materials required. Additional materials may be required for sites on poor soil conditions, sites closer to active faults, or for buildings with unusual structural framing configurations. These additional building factors were not considered in the original work or this paper.

The seismic requirement information provided considers each system or assembly separately and does not consider the potential interaction between the systems and assemblies selected. For example, although the material requirements for a brick veneer cladding itself do not change based on seismic region, the seismic load on a building with brick veneer cladding will be higher than for an identical building with a lighter cladding material such as wood siding since seismic loads are also a function of the building's overall mass.

Seismic requirement information for concrete and wood framed shear walls is based on the assumption of a "typical" shear wall design approach. Buildings with a large number of openings and relatively fewer shear walls will require higher lateral load capacity per linear foot of shear wall resulting in a greater increase in materials per linear foot of shear wall for seismic requirements. For the residential single-family home designs contrasted later in this paper the openings were not particularly large. Thus, no extraordinary shear design values were required.

The following lists the various structural systems supported by the Athena Institute's Impact Estimator for buildings software that were reviewed for seismic detailing. Note the software also supports envelope material specifications (e.g., gypsum wallboard, insulation materials, and claddings), but these were only considered for their respective dead load affects.

12) Slab on grade and footings:
    a) Concrete slab on grade
    b) Concrete strip footing
    c) Concrete column footing
13) Wall systems (exterior and interior)
    a) Wood stud
    b) Concrete block
    c) Cast-in-place concrete
    d) Precast cellular concrete
    e) Tilt-up concrete
    f) Curtain wall
    g) Insulated concrete forms (ICF)
    h) Steel stud
14) Beams and Columns
    a) Concrete beam and column
    b) Glulam beam and wood column
    c) WF beam and HSS column
15) Floors and Roofs
    a) Concrete hollow core
    b) Concrete flat plate on columns
    c) Concrete flat plate with drop plate on columns
    d) Precast double T
    e) Parallel chord wood truss with wood web and plywood deck

f) Parallel chord wood truss with steel web and plywood deck
g) Pitched chord wood truss
h) OWSJ, steel deck, concrete topping
i) Steel joists, plywood deck
j) Wood glulam with solid wood deck
k) Wood-I with plywood deck
l) Wood joists with plywood deck

Results: Seismic Requirements

The seismic requirements for one to two-story wood framed structures generally do not govern design. We therefore have not listed additional typical seismic requirements for one to two story dwellings within the table below. This is based on the use of conventional light-frame construction (prescriptive design) for seismic design categories A, B, C, D or E (as classified by IBC). We note that there are some additional prescriptive requirements for one to two story structures in seismic categories D or E. For a typical structure, however, with average size rooms and gypsum sheathed interior walls, the effect on material usage is limited to increased shear wall design and we have applied the typical "50% all load bearing walls are shear walls" as the governing factor for residential structures and some minor changes in footing requirements (see Table 1). It is assumed that masonry veneer is not used on one-two story structures in seismic categories D and E based on typical building types in these areas.

Table 1 outlines the seismic requirements for systems and assemblies typically used in low-rise commercial and low rise residential buildings for Seattle and Los Angeles, relative to non-seismic designs. Overall, the study's findings reveal that seismic requirements in Los Angeles exceed those of Seattle. Typically, high mass load bearing concrete assemblies require additional sizing and/or reinforcement (e.g. perimeter strip footings, concrete masonry and cast-in-place walls) relative to other assembly designs. Concrete column and beam or slab systems are gravity systems and these structures rely on shear wall placement and design to resist seismic forces. Steel framed buildings typically use a combination of heavier column and beams with greater reinforcement at horizontal mergers. Light gauge steel is typically only used as an infill wall assembly, which is governed by wind loads. However, for purposes of comparing light gauge steel framing with wood framing in the single-family home design, the steel framing gauge was increased (on average) to 18 gauge from 20 gauge and 50% of the exterior walls were designed as shear walls incorporating compression posts and tie down hardware – see wood wall design specifics. Wood assemblies generally incorporate greater lateral resistance methods – e.g., additional perimeter sheathing nailing patterns, more bracing (additional wood materials) or in the case of shear walls more nailing and materials (wood bracing and steel compression posts, anchor bars and tie downs). Roofing systems are generally governed by gravity dead loads and thus are not seismic assemblies.

As discussed previously seismic design is a function of the dead load of the building and its ability to resist lateral loads. The greater a building's mass the greater the lateral load resistance required. Much of the seismic lateral load resistance is provided by shear wall design and these and generally exterior wall systems also act as the tie down mechanism between the foundation up through the building to its roof structure.

Table 1: Location Specific Incremental Seismic Requirements

System ID	Description of the System	Additional Seismic Requirements in Seattle	Additional Seismic Requirements in Los Angeles	Remarks
1 a)	Concrete Slab on Grade	Nil	Nil	Same as gravity design
1 b)	Concrete Strip Footing For concrete walls	• Vertical dowels for zone bars • Longitudinal and transverse top & bottom rebar **20% increase in concrete footing size and 20% increase in rebar**	• Vertical dowels for zone bars. • Longitudinal and transverse top & bottom rebar. **30% increase in size of footing and30% increase in rebar**	All concrete walls are shear walls.
1 c)	Concrete Strip Footing for Stud Framed walls	**10% increase in concrete footing size and 10% increase in rebar**	**15% increase in size and rebar**	Material increase based on design with 50% of load bearing walls as shear walls Requirements apply to shear wall footings only
1d)	Concrete Column Footing	Nil	Nil	Columns are typically used for gravity loads and do not resist lateral loads.
2 a)	Wood stud – Exterior and Interior	Note that there are some additional elements common in these walls, including compression posts and tie-downs, although these are only typical in shear walls. Changes to all walls = Wood: 0.218 x h x L (bdft) Steel: .033 x h x L (kg) For additional nailing of plywood sheathing – see 5d	**50% more materials than that required for Seattle for anchor tie down system and compression posts.** For additional nailing of plywood sheathing – see 5d	Material increase based on design with 50% of load bearing walls as shear walls Assume plywood sheathing. For shear walls Requirements apply to shear walls only
2 b)	Concrete Block	Additional rebar and grout fill required. All cores filled with grout. 1 #5 Vertical bar in each cell (200mm o/c) Typical design for non-seismic zones is (1) #5 bar in grout filled core @ 1200mm o/c **500% increase in grout and steel.**	**50% more rebar than that required for Seattle**	Assumed single storey commercial building, 14 ft high, 10 inch block • #5 bar in each cell in Seattle • #6 bars in each cell in Los Angeles • No change in horizontal reinforcement

System ID	Description of the System	Additional Seismic Requirements in Seattle	Additional Seismic Requirements in Los Angeles	Remarks
2 c)	Cast in place concrete wall	Zone reinforcement required at each end of wall extending 2 ft back from end of wall. • Zone reinforcement - #8 bars @150mm o/c both faces. • Zone ties required. - #3 bars for ties **35% more rebar**	50% additional steel to Seattle. (Zone reinforcement extending 3ft back from end of wall) **50% more rebar**	Assume ordinary reinforced concrete wall. Up to 4 stories high, 30 ft long wall. Non-seismic reinforcement: #5 bars @ 300mm each face. #5 @ 300mm o/c horizontal both faces. No change in horizontal vs. non seismic.
2 d)	Precast Cellular			See Tilt–up in 2e
2 e)	Tilt-up concrete	Same as 2c but w/ #6 instead of #8 **20% more rebar**	Same as 2c but w/ #6 instead of #8 **30% more rebar**	Up to 2 stories. Additional hardware required for connection to the footing.
2 f)	Curtain wall	Nil	Nil	Generally governed by wind
2 g)	ICF concrete wall	Same as 2c but w/ #6 instead of #8 **20% more rebar**	Same as 2c but w/ #6 instead of #8 **30% more rebar**	
2 h)	Steel studs	This is an atypical wall assembly. Load bearing SS walls would require additional cross bracing, anchors, and gusset plates. Total weight increase of 16 kg per m2 of wall.	This is an atypical wall assembly. 50% more materials than that required for Seattle for cross bracing, anchors, and gusset plates.	Generally used as in-fill walls, and governed by wind.
3 a)	Concrete Beams & Columns	Nil	Nil	Beams and columns support the gravity loads only. Shears walls should be added for the lateral loads.
3 b)	Glulam beams & wood columns	Nil	Nil	These elements are generally used for gravity loads, not seismic loads.
3 c)	WF beams & HSS columns	25% of the columns will have 33% additional weight **Use 0.7 kg/m (column height) per column additional weight**	25% of the columns will have 50% additional weight **Use 1.2 kg/m (column height) per column additional weight**	Assumed a single storey commercial steel building with cross bracing all four sides. Assumed 100 ft x 100 ft plan area, 14 ft high with two braced bays in each side.

System ID	Description of the System	Additional Seismic Requirements in Seattle	Additional Seismic Requirements in Los Angeles	Remarks
4 a)	Concrete Hollow core	Nil	Nil	• Not common in high seismic zones • Generally designed for gravity loads only. • The topping will have steel reinforcement for gravity loads and for diaphragm connections.
4 b)	Concrete flat plate on columns	Nil	Nil	Not used as a lateral load resisting system in a building.
4 c)	Concrete flat plate with drop panel on columns	Nil	Nil	Same as above
4 d)	Precast Double T	Nil	Nil	See Hollow core above for comments
4 e)	Parallel chord wood truss with wood web and plywood deck	**Up to 100% increase in the nailing of the plywood sheathing edges with blocking between the trusses**	**Up to 200% increase in the nailing of the plywood sheathing edges with blocking between the trusses**	Typically the sheathing edges are nailed @ 150mm o/c. for non-seismic zones.
4 f)	Parallel chord wood truss with steel web and plywood deck	Same as 4e above	Same as 4e above	Same as 4e above
4 g)	Pitched chord wood truss	Nil	Nil	Primarily carries the gravity loads Wind load governs in most cases.
4 h)	OWSJ steel deck, concrete topping	**Up to 100% additional deck to joist weld connections**	**Up to 100% additional deck to joist weld connections**	Puddle weld every flute instead of every other flute.
4 i)	Steel joist plywood deck	See 4e above	See 4e above	See 4e above
4j)	Wood Glulam with solid wood deck	Nil	Nil	Generally the decking is installed with a standard connection for all conditions. Not suitable for high seismic applications
4 k)	Wood –I with plywood deck	See 4e above	See 4e above	See 4 e above
4 l)	Wood joists with plywood deck	See 4e above	See 4e above	See 4e above

Results - Sensitivity Analysis Of Seismic Adjusted Single-Family Residential Structures

Given the prescribed seismic requirements noted above a sensitivity analysis was prepared to determine the environmental life cycle impact implications of seismic adjusted single-family home construction in Seattle and L.A. relative to non-seismic home construction.

The relative environmental implication of seismic requirements is based on an earlier CORRIM wood and light gauge steel single-family home design modeled in the Athena Impact Estimator software as built in Minneapolis (Lippke et. al. 2004). The original Minneapolis single-family house design was adjusted slightly to better reflect building practices in western USA; i.e., in place of a full basement a crawl space was specified instead. The home is a 204 m^2 (2400 sq. ft.) two-story structure.

In order to complete the sensitivity analysis we adjusted each base material assembly design determined for a non-seismic zone (i.e., Minneapolis) to reflect the seismic requirements for the wood and steel material designs in Seattle and L.A. In order to concentrate the analysis on the seismic changes we modeled each seismic design in Minneapolis (the same as the base design) to keep all the modeling parameters constant. Hence, these sensitivity results do not reflect Seattle or L.A. location specific variables other than seismic requirements. The life cycle impact analysis was primarily focused on two measures – embodied primary energy demand (GJ) and associated greenhouse gas emissions or global warming potential, GWP, (CO_2 equivalent kg) as both energy intensity and climate change are two topical issues of great concern.

Table 2 summarizes the results for each material design within and across building codes. Moving from Minneapolis to Seattle and then to the L.A. code, both the wood and steel designs show significant increasing primary energy demand and global warming potential with increasing seismic requirements (Figures 1 and 2). Typically to satisfy increasing seismic requirements more steel materials (anchor bolts, tie down rods, reinforcement bar and fasteners) are used to stiffen wall assemblies and tie the roof, wall and foundation together to better resist shear loads.

Table 2. Single-Family Design Sensitivity Results – Primary Energy & Global Warming Potential for Three Building Locations

(Structural effects only)	Primary Energy GJ	GWP CO2e kg	Within Design Primary Energy	Within Design GWP	Between Design Primary Energy	Between Design GWP
			% difference		% difference	
Wood Design Minneapolis	279.4	15,810	(base)	(base)	(base)	(base)
Wood Design Seattle	442.2	29,480	58%	86%	(base)	(base)
Wood Design Los Angeles	486.9	31,370	74%	98%	(base)	(base)
Steel Design Minneapolis	413.2	26,530	(base)	(base)	48%	68%
Steel Design Seattle	582.2	41,440	41%	56%	32%	41%
Steel Design Los Angeles	634.2	44,300	53%	67%	30%	41%

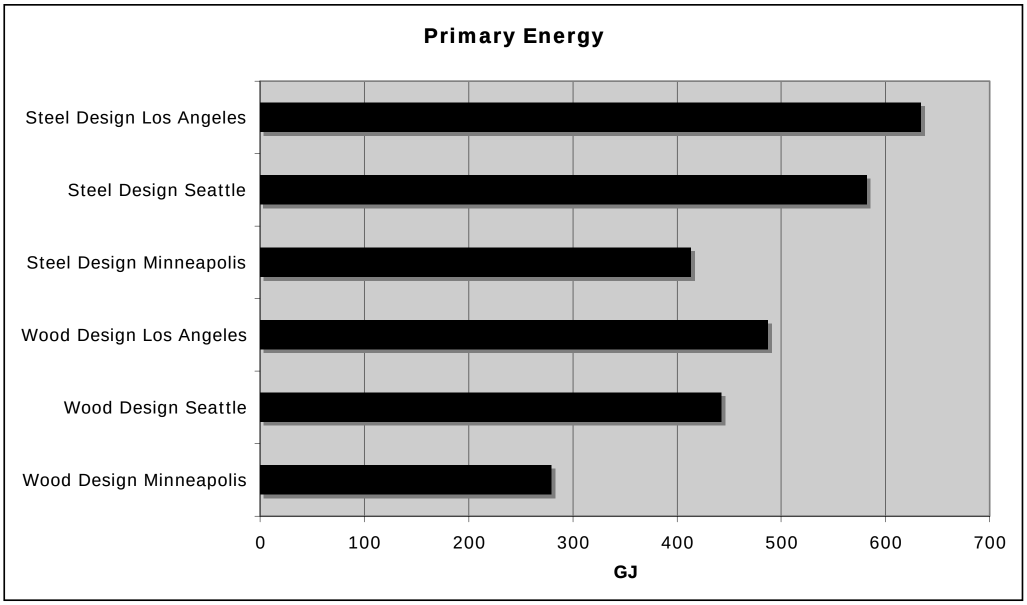

Figure 1. Primary Energy Demand (GJ) – for Three Single Family Design Building Locations

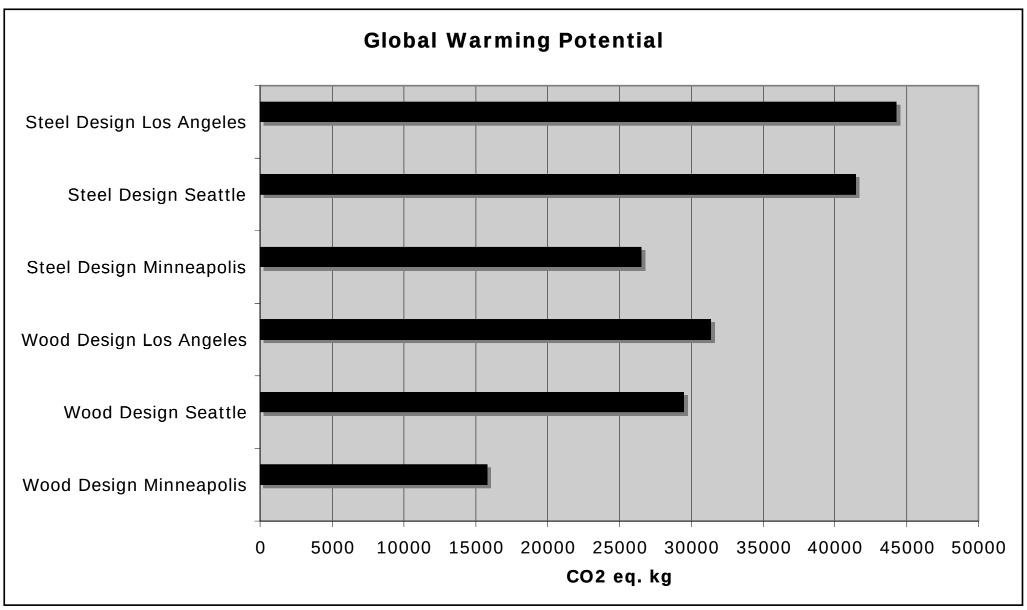

Figure 2. Global Warming Potential (CO2 eq. kg) – for Three Single Family Design Building Locations

Relative to wood, steel products generally embody more primary energy and emit more greenhouse gas emissions. So while the change in absolute differences in primary energy use going from non-seismic to more seismic sensitive locations is similar across wood and steel designs, the proportional effect across material designs is greater for the wood design than it is for its higher embodied energy steel counterpart. The within wood design results indicate up to 74% and 98% change in embodied energy and GWP, respectively even though the absolute value increases are slightly lower than for the steel design. While the steel design percent change varies between 41%-53% and 56%-67% for primary energy and greenhouse effect, respectively. The difference in primary energy demand and GWP are more muted between the two material designs moving from non-seismic to more seismic sensitive building locations, with wood showing significantly lower, but declining embodied energy and GWP effects.

Table 3 includes the impacts for air pollution, water pollution and solid waste as other life cycle burdens of frequent interest. Figure 3 compares directly the impact on energy, GWP and air pollution. The air pollution impacts are directly proportional to the energy impacts. The GWP impacts are larger than the energy impacts because many of the materials used to meet seismic codes are more fossil intensive than wood.

Table 3. Seismic Code Impacts on Minneapolis Single Family House Design for Seattle and Los Angeles Codes

	Energy	GWP	Air Pollution	Water Pollution	Solid Waste
Wood Frame	GJ	$kgCO_2$	kg	index	
Minn Code	279,397	15,810	3,167	12	7,300
Seattle Code	442,172	29,474	5,082	12	8,955
LA Code	486,930	31,371	5,368	13	9,336
Steel Frame					
Minn Code	413,191	26,533	4,768	68	8,034
Seattle Code	582,205	41,438	6,818	83	9,823
LA Code	634,226	44,300	7,228	91	10,390

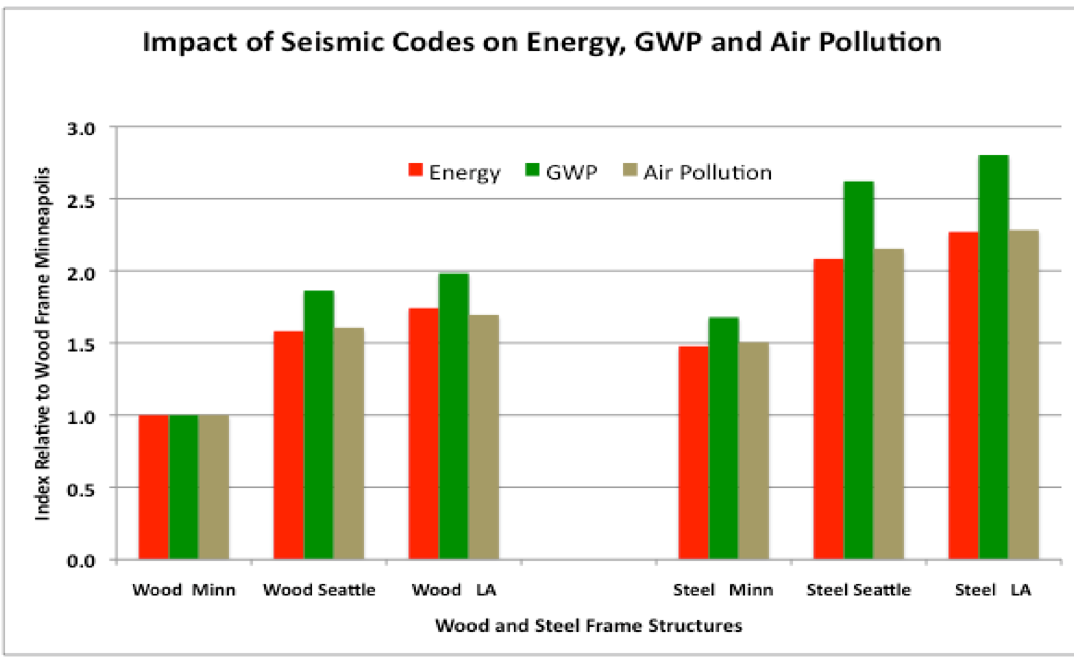

Figure 3. Impact of Seismic Codes on Energy, GWP and Air Pollution

While the analysis did not include the carbon stored in wood products as an offset to the carbon emissions from processing, the change in wood use is not great and hence would not likely have a material impact on the change in GWP. There is also little impact on solid waste which is dominated by on site cutting and the increased use of fasteners are pre-cut.

Finally, while the impact of steel framing on water pollution based on EPA toxicity standards driven by cyanide as the most toxic emission is substantially larger than for wood framing where phenols are most toxic, the percentage increase in water pollution from seismic codes is significantly less than the increase for energy or GWP (Figure 4).

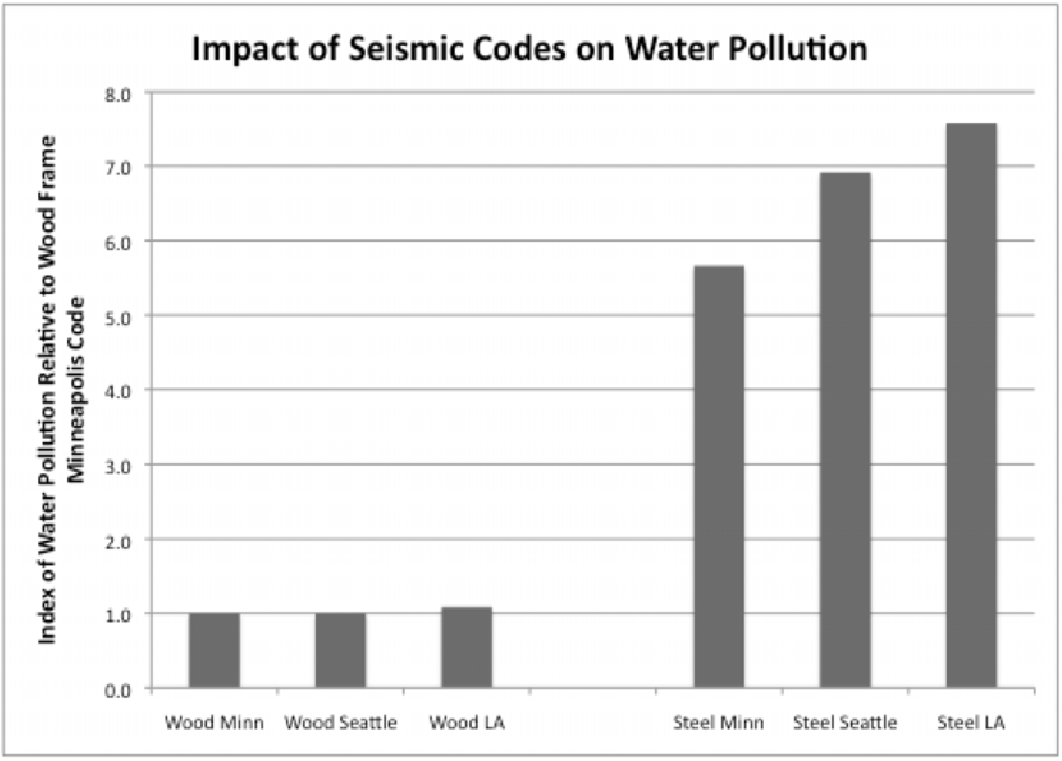

Figure 4. Impact of Seismic Codes on Water Pollution

Conclusions

Seismic design requirements are significant from a material use perspective and significantly alter the environmental impact of residential structures, both on an absolute and relative basis, regardless of the primary material design. While material selection is an important factor in reducing environmental burdens, seismic requirements increased the burdens for the designs evaluated here providing some motivation for considering alternative structural designs that may use less fossil intensive materials in order to achieve the same strength objectives.

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