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Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings

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ABSTRACT

Design for Deconstruction (DfD) is a design approach that enables reuse of durable building components, including structural materials, across multiple building projects. An important DfD strategy is the use of prefabricated modular building assemblies and reversible connections, in contrast to cast-in-place composite systems that must be demolished at building end-of-life. In this paper we evaluate a novel DfD flooring system consisting of pre-cast concrete planks and clamped connections. Life cycle energy and environmental benefits of using this DfD system are evaluated using life cycle assessment (LCA) across four impact categories of interest to the building and construction sector including fossil fuel use, greenhouse gas emissions, respiratory effects, and photochemical smog formation. Eight different DfD building designs are tested for 0–3 reuses compared with a traditional structural design, with energy and environmental benefits accruing from substitution of avoided structural materials. Designs reflect expected loads and current code requirements, while the additional time required for deconstruction of DfD buildings is accounted for in the construction schedules. Monte Carlo simulation is used to generate 95% confidence intervals for the results. In general, DfD designs result in higher initial (original building) energy use and environmental impacts, but have statistically lower impacts than traditional designs if flooring planks are used at least once. Reusing planks three times as designed decreases impacts by a mean value of of 60–70%, depending on the building configuration and impact category. Energy use and environmental impacts from eventual recycling and/or disposal of the reusable components are significant, and emphasize the relative benefits of reuse over recycling.

1. Introduction

1.1. Design for Deconstruction

Construction and demolition (C&D) waste in the United States totaled 534 million short tons (484 million metric tons) in 2014, more than 90% of which is debris generated during demolition [1]. Recycling and reusing C&D waste conserves landfill capacity and reduces energy and environmental impacts by avoiding the need for new materials [2,3]. Embodied energy typically amounts to < 20% of the total life cycle energy of modern buildings [4,5]; however, as more energy efficient buildings are designed and built and the demand for operational energy is reduced, the proportional impacts of embodied energy will increase, as will the benefits of the reuse of building materials.

The desire to reduce building energy consumption and material waste through reuse motivates the exploration of Design for Deconstruction (DfD) of buildings. In DfD, salvaged materials from old buildings are repurposed directly in new projects, thus eliminating the costs of waste disposal, new material manufacturing, and the processing associated with recycling. Recycling of building materials still incurs environmental burdens, as materials must be collected, sorted, transported, cleaned/pre-processed, and then remanufactured. In many cases, building materials are downcycled into products of lesser value, such as concrete crushed and used as road base material. For metals such as structural steel, remanufacturing requires energy-intensive remelting. For these reasons, direct reuse is preferred to recycling, particularly when the locations of deconstruction and new construction are relatively close [6].

DfD, first proposed for modern buildings in the 1990s [7], aims at designing buildings so that durable materials can be easily reclaimed and repurposed at the end of the building's service life. At the time of deconstruction, cost savings from DfD can be accrued both by the

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owner of the original building who can sell reusable components and by the owner of the new building who has access to high-quality but discounted building components. In addition to cost savings, updates to building codes (ASHRAE 189.1 and IgCC) and green building certifications such as LEED v4 also encourage building owners, contractors, architects and engineers to incorporate DfD into the design of new structures through targets on C&D waste generation and use of local building materials.

Kibert [7] has discussed numerous challenges that exist for DfD, such as reliance on irreversible connections/fasteners or composite systems that require destructive demolition, a lack of tools for deconstructing buildings, the low disposal cost for demolition waste, the need for building codes addressing how to design with reused materials, and the inadequacy (at the time) in establishing the environmental and economic benefits. Time is also a significant factor for deconstruction and should be provided for in the overall project scheduling [7]. Additional DfD construction management challenges discussed in a set of case studies by Gorgolewski [6] included the need for rapid testing of deconstructed components to establish their structural characteristics and coordinating demand with supply in space and time (or providing storage capacity). It was beneficial for design engineers and architects to communicate and develop working relationships with local demolition and salvage contractors to obtain an inventory of available components.

Durmisevic and Brouwer [8] argued that traditional design of buildings focused on the short-term performance, such as the optimization of functions, costs, and construction schedules. Long-term durability of building components can be achieved when buildings are able to cater to the changing needs of their owners and occupants, with dynamic and flexible structures and components that can be disassembled, replaced, recycled, or reused. DfD design strategies include modular parts dry assembled on site, independence of various systems, application of parallel instead of sequential assembly/disassembly, and use of reversible mechanical connections.

Structural steel framing systems are particularly conducive to deconstruction at the end of the service life of a structure, so long as they have not been subjected to extensive permanent damage from an extreme hazardous event. A survey conducted by O'Conner [9] revealed that demolition of buildings in North America was rarely due to damage in structural systems and materials, but mainly because of the lack of maintenance for non-structural components, changing land values, and inability to meet current owners' needs. Composite structural systems use both steel and concrete, with concrete being subjected to compression and steel resisting tension. Steel frames are erected in place, with corrugated metal deck often laid atop the steel beams and girders, shear connectors shot onto the top flanges of the steel members, reinforcement laid in place, and a monolithic concrete floor slab cast in place. However, composite steel-concrete floor systems, by far the most ubiquitous type of structural steel framing for commercial and residential buildings, are not reusable at end-of-life. The integration of steel beams and concrete slabs via shear connectors inhibits the separation of the two materials, making impossible the deconstruction of the composite flooring systems and reuse of the structural components. Steel beams and shear studs can be recycled after being extracted from demolition debris, while concrete slabs are crushed for fill or making aggregates for new concrete. Conventional composite floor systems are therefore not the best choice for reducing the long-term environmental impacts of building materials.

1.2. Life cycle assessment (LCA) of buildings, construction, and deconstruction

The construction industry has begun to assess the energy and environmental impacts of design and material choices, including at building end-of-life, most commonly using life cycle assessment (LCA). LCA is an internationally standardized (ISO 14040:2006) quantitative method that accounts for resource use, emissions, and potential environmental and health impacts over the life cycle of a building, including extraction of raw materials, manufacturing and assembly of building assemblies, transportation, construction, building operation, maintenance, and eventual deconstruction or demolition. In this way, LCA models allow engineers, architects, and owners to examine environmental trade-offs associated with building materials, assemblies, or particular design features in a comprehensive, whole-building manner. The use of LCA can also prevent 'burden-shifting', where design decisions made to achieve one set of environmental goals actually cause unintended consequences to another set. LCA has been applied to buildings and construction, often examining specific building projects, with a variety of objectives. These include choosing among specific materials, examining trade-offs between embodied energy and operational energy, identifying 'hot-spots' (materials or stages that dominate a category of impacts) in the building life-cycle, and evaluating new methods of construction or structural engineering approaches [10,11].

Specifically, LCA has also been used to quantify the energy and environmental benefits of recycling and/or reusing building materials and components [12]. Several tools have been developed to assist in estimating benefits, either integrated in Building Information Models [13] or as stand-alone modules [14,15]. Case studies have considered both residential, wood-framed buildings [16] and commercial steel or concrete-framed structures [17], estimating the quantity of materials in a traditional building that could be recovered.

Conversely, DfD strategies focus on enabling reuse through design innovations. For example, using modular or pre-cast assemblies, shows benefits in terms of reduced life cycle energy use, construction waste, and/or better structural performance and reduced material requirements [18,19]. Of particular interest for the present work is a study from Lopez-Mesa et al. [19] that compared the environmental impacts of buildings with floor systems made up of hollow-core precast slabs and cast-in-place one way concrete. Though the pre-cast floors themselves were heavier and more costly than cast-in-place floors, their use required fewer beams, leading to fewer or lighter columns and a smaller foundation, and ultimately to lower embodied energy results.

1.3. Novel DfD structural system

As the most common type of structural steel framing used in commercial and residential buildings, the traditional steel-concrete composite flooring system makes efficient use of the two materials, with steel being subjected to tension and concrete resisting compression. However, in this system the concrete slabs are cast integrally with the supporting steel framing systems, inhibiting the separation and reuse of the structural components.

Novel structural system concepts have been developed for deconstructable steel and steel-concrete composite construction to facilitate DfD, coupled with the use of recycled materials in sustainably optimized construction. These new systems are designed to maintain the structural benefits of steel-concrete composite construction, such as enhanced flexural strength and stiffness, reduced steel beam size and weight, and ease of construction, while enabling disassembly and reuse of the structural components.

A deconstructable composite prototype is illustrated in Fig. 1; this concept was first introduced in Webster et al. [20]. The system consists of precast concrete planks and steel beams connected using clamping connectors. Frictional forces are generated at the steel-concrete interface to resist required shear flow and achieve composite action. Cast-in channels are embedded in the concrete planks to provide flexibility for where the beams intersect the planks and to allow for different beam widths. Tongue and groove joints at the concrete plank edges ensure vertical load transfer between adjacent planks and offer a level and well-matched top surface. The removable bolts in the clamping connectors enable the precast concrete planks and the steel beams to be disassembled and reused in future projects.