

Designing Structural Systems for Deconstruction: How to Extend a New Building's Useful Life and Prevent it from Going to Waste When the End Finally Comes

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PREFACE

This paper applies the emerging concept of Design for Disassembly (DfD) to building structural systems. DfD benefits the environment by simplifying building modifications and end-of-life disassembly. Buildings are more likely to be renovated, rather than replaced, when renovations are made simpler and less costly by the application of DfD. At the end of the building's life, materials are more likely to be salvaged or recycled if they can be easily removed and segregated. Structural systems generally account for well over 50% of a building's mass, so application of DfD to the structure is particularly worthwhile.

The authors, a structural engineer and a building dismantler, review the general concepts of DfD, and then apply DfD concepts to the most common structural systems and materials, including steel, concrete, wood, and masonry structures. Finally, the paper considers how DfD might be rewarded in a LEED credit.

1. WHY DESIGN FOR DECONSTRUCTION?

Although many of our country's politicians and economists champion consumption under the theory that it helps our nation's economy, one of the down-sides of consumption is the depletion of natural resources. To produce goods such as appliances, cars, toys, packaging, and buildings, we consume finite resources such as petroleum products, rocks and minerals, and water. Even renewable resources such as wood, grains, and animal products are finite. As the world's population continues to grow—it is not forecast to stop growing until the end of this century or later—and becomes more affluent—think of China—the squeeze on the earth's resources will continue to tighten, leading not only to environmental degradation, but potentially also to political instability and strife.

The question, then, is how do we meet the growing demand for consumption while tempering this demand for finite resources? A number of strategies come to mind: reduce the demand for material goods, make products that last longer so they do not require frequent replacement, produce products using more renewable materials and sources of energy, and reuse and recycle materials that have already been used, thus reaching for the ecological ideal of "closing the materials loop."

Buildings consume a large proportion of the world's resources. The statistics speak for themselves: buildings in the United States consume 40% of the nation's energy and 70% of its electricity (USEIA 2004). New construction, maintenance, and renovation of buildings account for 40% of the world's material flows (Roodman and Lenssen 1995). "Green" building owners, designers, and builders—"green" meaning buildings with reduced environmental impact—recognize that an essential part of our task is to work to reduce the consumption of finite

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resources, and the most effective way we can accomplish this goal with respect to construction materials is to start closing the materials loop.

In order of decreasing preference, used materials should be:

- Reused
- Recycled
- Used to generate energy
- Composted
- Land-filled

Reuse is the most desirable option because it is most effective in reducing the demand for virgin resources and reducing waste (Webster and Bronski 2005). By reuse or salvage (we use the terms interchangeably), we mean the reuse of a previously used item (brick, piece of lumber, steel column) with minimal processing. Contrast reuse with post-consumer recycling, wherein a used product is destroyed to manufacture a new similar or different product.

Material reuse considerations do not start when a building reaches the end of its life; improving the odds for material reuse starts when a building is designed. It starts with selecting materials that are reused or recycled (in order of preference), and with designing with the building's full life-cycle in mind. Designing for the full life-cycle means designing for durability, designing for adaptability, and designing a building that can be efficiently mined as a source of reused materials for new construction when it reaches the end of its useful life.

The application of the Design for Deconstruction (DfD) principle to buildings is challenging. Many building materials are not reusable. Often materials are interconnected in ways that make them difficult to separate and reuse even if they are theoretically reusable. The long lifespan of buildings makes it difficult to predict which materials will have salvage value and what technologies will be available to extract materials at the end of the building's life. Mainstream green building rating systems such as LEED do not include incentives for DfD. And financial incentives for DfD are difficult to quantify, although buildings designed for DfD should be easier to construct, perhaps saving up-front costs (Pulaski et al. 2003). But the environmental benefit is almost certain. If DfD strategies result in more adaptable buildings, more easily renovated buildings, more durable buildings, and buildings with more reusable materials at end-of-life, then environmental benefits will be realized, even if a small increase in materials may be needed initially.

The goals of this paper are to:

- describe building characteristics that facilitate deconstruction and increase the yield of salvageable materials;
- develop DfD strategies for new buildings;
- apply these strategies to structural materials, which comprise the greatest proportion of building materials; and

- consider some ways that LEED and other green building rating systems might encourage DfD.

In this paper, we rather single-mindedly address the topic of DfD at the expense of other green building strategies. Where appropriate, we touch upon instances where other design goals may trump end-of-life and adaptability goals. Green building design should be holistic; many different green building strategies should be considered to achieve the desired environmental goals. DfD should always be a design consideration, but not necessarily the overriding consideration.

2. CHARACTERISTICS OF BUILDINGS THAT ARE EASY TO DISASSEMBLE AND YIELD SALVAGEABLE MATERIALS

One of this paper's authors is an experienced professional dismantler. In his practice, he has found that certain building types, assemblies, and materials facilitate dismantling operations and material reuse.

2.1 What Works?

Certain building characteristics simplify the job of the dismantler, reducing the time and expense of salvaging the building materials:

- Transparency. Building systems that are visible and easy to identify.
- Regularity. Building systems and materials that are similar throughout the building and laid out in regular, repeating patterns.
- Simplicity. Building systems and interconnections that are simple to understand, with a limited number of different material types and component sizes.
- Limited number of components. This dismantler has found that it is easier to dismantle structures that are composed of a smaller number of larger members than a larger number of smaller members. Larger members tend to resist damage more easily during the deconstruction process and can be removed more quickly from the structure. For example, it is easier to deconstruct a timber-framed wood structure than a wood structure framed with dimension lumber. Note that in cases where deconstruction will likely be undertaken using primarily hand-labor rather than large machinery, it may be appropriate to design with smaller, lighter members.
- Easily separable materials. Materials should be easily separable into reusable components. Mechanical fasteners are preferable to adhesives. Composite materials are a difficulty unless the composite assembly has reuse value as an assembly.

An example of a building type that epitomizes these criteria is the traditional brick and timber New England mill building (Figure 1). During the period from the late 1800s to early 1900s these buildings were built in every New England mill town. Many today are enjoying a resurgence in popularity after many years of underutilization following the departure of most of the manufacturing industries to regions with lower costs. These buildings are readily adaptable due to some of the very qualities that make them easy to deconstruct: their simple layout, transparency, and regularity.

Buildings from this era typically are constructed of brick masonry bearing exterior walls, timber floor framing and interior columns, and 3 in. wood decking. All of these components can be easily separated without significant damage and reused. The lime mortars used to bind the bricks is softer than the brick and easy to remove. These materials all have resale value in today's salvaged building material marketplace.



Figure 1: Dismantling a New England Mill Building

2.2 What Doesn't Work?

Conversely, the author has found that some building types and materials are difficult or impossible to deconstruct or have no reuse value if deconstructable:

- **Complex Buildings.** Buildings where the structural and other systems are difficult to understand or hidden are challenging to deconstruct.
- **Non-Standard Components.** Custom components may have no use in any other building. Imagine trying to reuse the steel framing making up the exterior envelope of the Bilbao Guggenheim Museum or Stata Center at MIT (not to pick on Frank Gehry!).
- **Composite Materials.** It may not be possible to disassemble certain types of composite construction. For example, how would one take apart a reinforced, grouted CMU wall with the intent to reuse the CMU block, grout, and reinforcement in another project?
- **Mixed Material Grades.** Materials that look similar but have different properties have less value. For example, a building framed using multiple wood species or steel grades yields a potentially confusing array of materials that may not be as effectively reused as materials from a building constructed using a single material grade. Identification of unlabelled materials is especially problematic, and may result in the better grades getting lumped with the lesser grades for the sake of simplicity. Better to have one large batch of similar material than many smaller batches to simplify sorting and identification efforts and increase resale value.

- Mixed Building Systems. Buildings constructed using multiple structural systems.
- Environmental Hazards. Hazardous materials such as asbestos and lead that require special handling and worker protection.

3. APPLYING THIS KNOWLEDGE TO NEW DESIGN

Using our dismantling and structural engineering experience, and drawing upon published literature, we have developed guidelines for designing new structures for deconstruction.

3.1 Desired Architectural Characteristics

- Use a simple, regular layout with similar bay sizes throughout. The dismantler will find similar member types and connections from one end of the building to the other. The building framing will yield many identical members (i.e. same cross-section and length), which will be easier to sort, sell, and reuse.
- Layer building systems. When mechanical systems and envelope components are intermingled with structure, it is difficult to replace these systems during the building life and difficult to extract the structural elements at the end of the building's life. For example, in conventional wood-frame residential construction, wiring and plumbing is threaded through the wood framing, damaging the framing and requiring more labor to separate the components at end-of-life.

3.2 Desired Structural Characteristics

- Use common, standard shapes and connections; minimize the number of different member sizes.
- Use removable fasteners; avoid adhesives. The best types of connections are friction connections such as clamps, since they do not require holes or notches to be cut into connected members. It is also easier to determine the connection stability during disassembly with discrete mechanical connectors compared to bonded connections. For example, when separating two pieces of steel that are bolted together, it is generally visibly evident when the connection will become unstable, whereas when cutting apart welded members the point of instability may come as a surprise (Chini and Balachandran 2002).
- Design using fewer large members rather than many small members (although more difficult to handle without large equipment).
- Avoid using multiple types of structural systems.
- Use salvaged materials, if available. If they were salvaged once, they can probably be salvaged again.
- Avoid composite systems unless the combined system can be reused. For example, structural insulated panels, though a composite of rigid insulation and wood-based sheathing, could be removed from an existing structure (if joined using removable fasteners) and reused elsewhere.

- Select materials with reuse potential based on current practice. More reuse options may be available in the future, but the range of future options will likely include those materials that are reusable today.

3.3 Other Design Issues

- Consider handling and safety. Think about how the structure will be dismantled. Provide lifting points and safety tie-offs to aid dismantling where possible. Provide areas where deconstruction workers can safely stand and work (e.g. Hinze 2002).
- Label materials. Labels should include information that will simplify reuse. For instance, the label may include the date, material grade, material strength, and any special handling instructions.
- Safeguard original drawings. Provide a specific, labelled, on-site storage place for as-built drawings.
- Design using materials that are non-hazardous, non-toxic, and durable.

4. STRUCTURAL MATERIALS

We now apply the guidelines outlined above to design using the major structural materials: wood, steel, masonry, and concrete. Many of the references listed at the end of this paper contributed to these ideas.

4.1 Wood

Wood structural systems rate highly for end-of-life reuse potential. As described above, old mill buildings framed with large wood timbers are now treasure troves of material for new construction. Examples of new structures constructed using salvaged timbers abound, including the farm market shown in Figure 2. Unfortunately for structural engineers, much of this salvaged timber does not end up in structures, but instead is sawn for flooring and furniture. This paper's structural engineer author considers this a down-grading of the material and would prefer to see such members reused for structural applications, particularly since these large members could easily be reused a number of times if kept intact, but are more difficult to salvage if used as flooring or other finishes.

While large timbers are a proven source of structural salvage, dimension lumber has proven more challenging, although the authors know of examples where 2x members have been successfully reused (see e.g. Kernan 2002). In large part it is a problem of economics. Extracting dimension lumber intact is time-consuming. Care must be taken in disassembly to avoid damaging the members, and nails must be extracted. Frequently the ends of the members are damaged due to nailing, and we discussed above the damage that plumbers and electricians can do. However, we know of no technical obstacles to salvaging dimension lumber. It can even be graded, and the Forest Products Laboratory is working on a standard specifically designed for grading salvaged lumber.

If virgin lumber increases in price, the equation could change, and salvaged dimension lumber could be more competitive. The designer can take steps to make the deconstruction of wood-framed residential and small commercial structures more likely. For example, panelized construction may allow complete panels to be reused, or, if not reused as a whole, to be more easily removed from an existing structure and deconstructed on the ground, where the work

could be done more safely. Instead of nails, screws and bolts—which are easier to remove—may be specified at connections.



Figure 2: Farm Market Constructed with Salvaged Timber

We summarize our wood-framing suggestions below:

- Use screws and bolts instead of nails. New connection techniques are required that lessen wood damage. Industry-standard bolting patterns would be helpful.
- Use robust moisture management techniques to protect wood from decay and insect damage.
- Use timber-frame construction instead of dimension lumber. Avoid fragile members such as engineered wood I-joists.
- Keep services (plumbing, electrical, HVAC) separate from structure.
- Label members with species and grades.
- Consider panelized construction, particularly at roofs, to permit final deconstruction on the ground.
- Avoid adhesives, such as when fastening floor sheathing to joists.

4.2 Steel

Steel framing is also a strong candidate for reuse. In today's economy, however, steel is hardly ever salvaged, but rather separated from other materials and recycled. Salvaging is a better option environmentally than recycling, and, when designing for deconstruction, the engineer should seek out ways to improve the deconstruction cost equation.

Bolted connections make deconstruction easier, but members that had been bolted could require more patching during refabrication. Welded connections offer the benefit of requiring fewer modifications, such as bolt holes, to the connected members, but are more difficult to deconstruct. Ultimately, reliable clamped connections need to be developed (along with code-approved design procedures) to minimize fabrication modifications, such as bolt holes. Selecting member sizes and connection geometries that minimize the use of stiffeners and other welded accessories will also facilitate reuse. When using welded connections, design the welded components to be easily separable without damage to the connected members.

If, at the end of its life, the entire building frame is dismantled and re-erected elsewhere, either as a stand-alone building or as part of a larger building, then bolted connections are certainly superior to welded connections, because there is no need to refabricate the steel. Many of the case studies cited in the literature follow this model (e.g. Pulaski et al. 2004). The building shown in Figure 3 was disassembled by a contractor and moved from West Dover, Vermont to Brattleboro, Vermont. It was originally a theater in a condominium complex, and was slated to become a mixed-use building with offices and daycare facility.



Figure 3: Dismantling of Steel-Framed Building for Reuse

Another development that could be explored would be to establish a kit of parts to be used in steel-framed buildings. The idea would be to limit the number of shapes and lengths used in building construction and to establish connection rules and types that would allow reuse without any additional modification, much like the set of parts included in an Erector set. In this scenario, the designer might have a 30-foot span with a certain loading. Standard members might come in 30-foot or 30.5-foot lengths with a series of bolt holes at standard gauges pre-drilled in each end and at standard spacings along their length. The designer would select the size and length needed for the floor system design and select a standard connection that would work with the pre-drilled holes. Certainly this approach would be too restrictive for many signature building projects, but for many routine buildings it could be acceptable.

Light-gage steel members, like thin engineered wood members, are difficult to dismantle, store, and ship without damage.

We offer the following recommendations for DfD using steel structural systems.

- Use bolted connections. Explore using clamped friction connections.
- Avoid conventional composite floor systems using welded studs and cast-in-place concrete. New systems using bolted or clamped fasteners and precast elements need to be developed.
- Use precast decks.
- Use common shapes and avoid short filler pieces.
- Use regular spacing.
- Mark steel grades and shape designations on members.
- Seek alternatives to spray-on fire-proofing. Although spray-on fireproofing no longer contains asbestos, it is difficult to remove from steel framing. If left on salvaged members, it adds shipping weight and volume, can be damaged during transport, and is an impediment to refabrication.

4.3 Masonry

Masonry has a long history of reuse. Stones used in ancient buildings were often reused in new construction as a matter of course. Why quarry and cut new stone if it's available in a tumble-down, abandoned building next door? Stone is durable and easily deconstructed when sourced from buildings using traditional mortars with no portland cement.

Used brick is one of the most popular materials available in today's salvaged material marketplace. Salvaged brick has a warm and comfortable appearance that is difficult to recreate in mass-produced modern brick. The reason it can be successfully salvaged is that the historic lime mortars are softer than the brick and can be easily removed.

Unfortunately, it is extremely difficult to separate portland cement mortars from brick and other masonry units, almost certainly ensuring that masonry constructed today and over the past eighty or so years will not be salvaged. Furthermore, much of today's masonry construction is steel-reinforced. Building codes require that structural masonry in seismically active regions be reinforced to make it safer during earthquakes. The reinforcement is typically embedded in portland cement grout, making it impossible to salvage any of the constituent materials.

Thus structural masonry, as currently constructed, is a poor choice for use in buildings designed for deconstruction. New and innovative ideas are needed to make masonry salvageable again. Here are some considerations:

- As noted above, avoid portland cement mortars. No cost-effective technology is currently available to separate the mortar from the brick.
- Consider using lime mortars. Lime mortars have been used for hundreds of years and are regaining popularity, especially for historical renovation projects. Use in new construction should be investigated. Lime mortars generally have adequate strength to

be used in veneer and bearing wall applications. Durability, water-resistance, and maintenance need to be addressed.

- Avoid using grouted reinforcement. Designers should investigate using unbonded post-tensioned reinforcement in hollow masonry construction.
- Investigate using mechanical fasteners to secure brick masonry in place of mortar. Renzo Piano's IRCAM facade, for instance, uses this concept.

4.4 Concrete

Concrete is the most challenging of the major structural materials to design for future reuse. It is difficult even to imagine how cast-in-place concrete members could ever be salvaged. The structure is formed of one contiguous whole with no convenient joints where it can be separated. Structural members are heavy and difficult to move. The structural components are often custom-designed for their application. And it is impossible to see how the members are reinforced from the outside, so the future engineer will not have the information on strength and serviceability to be able to efficiently reuse the member. In the hierarchy of post-use options (see Section 1), the highest option for cast-in-place concrete—and a common practice even today—likely will be recycling.

Precast concrete offers greater reuse potential than cast-in-place concrete. Precast often comes in standard sizes and with standard amounts of reinforcement. Precast members are often joined together using mechanical fasteners. One problem is that cast-in-place topping slabs are often placed over precast floor members.

Strategies for DfD with concrete construction should include the following:

- Avoid cast-in-place members.
- Fasten precast members together with removable, durable, mechanical fasteners. Stainless steel is a good material choice for fasteners. Allow for thermal movement at connections so members do not become severely cracked.
- Develop new systems for connecting together precast plank and tees to replace topping slabs. In-plane diaphragm forces and out-of-plane shear forces can be resisted using mechanical fasteners. Removable materials such as plywood on sleepers may be used to provide a smooth sub-floor. In parking garages the precast joints may be left exposed.
- Indelibly label each member. The label should include concrete strength and member reinforcement.
- Consider eliminating basements and below-grade construction where possible. Foundation walls and deep footings are unlikely to be salvageable. Precast slabs-on-grade, precast foundation walls, and shallow precast footings have a greater likelihood of salvage.

5. “GREEN” STRUCTURAL ELEMENTS THAT ARE DIFFICULT TO REUSE

DfD needs to be weighed against other sustainability goals. Some of the strategies described above may result in greater initial material use, for instance. A design team may accept this

consequence if it deems future reuse to be a higher goal. A 10% increase in steel weight, for example, pales in comparison to the 50% savings in steel consumption that is achieved if the steel is reused just one time.

Some materials that may improve energy efficiency or reduce material use—both valid green building goals—are not the best candidates for future reuse:

- Insulating Concrete Forms (ICFs): Offer good thermal performance and eliminate formwork, but what happens when you want to take it apart?
- Engineered wood I-joists: Offer excellent material efficiency by concentrating the wood in the flanges, where it is needed to resist bending, and utilizing small trees. Wood I-joists are deconstructable, but greater care is needed to avoid damaging them compared to other wood products.
- Cast-in-place High-Volume Fly Ash concrete: Offers much improved environmental performance compared to 100% portland cement concrete, but still difficult to salvage.

The building designers should evaluate complete building life-cycle environmental impacts on a case-by-case basis to determine when and where the use of materials such as these are appropriate.

6. LEED

LEED does not presently offer any credit for DfD. The Materials & Resources category would appear to be the logical place to include a point, either as a stand-alone credit or as a multi-part credit under Resource Reuse (Credit 3). The primary difficulty (other than gaining the popular support to institute such a credit!) is to find a way to quantify DfD. Certain aspects of DfD may be quantifiable, but discussion is needed as to whether the measures are sufficient to earn a LEED credit. For example:

- Use a minimum percentage of reusable building components (by weight). Only components that meet the following reuse criteria qualify:
 - Components that are field-connected using easily removable mechanical fasteners. Exclude materials connected using field-installed adhesives or welds unless they may be easily removed to permit material reuse. Use screws and bolts in wood-framed construction (avoid nails).
 - Exclude cast-in-place concrete above grade.
 - Exclude grouted, reinforced masonry and masonry laid in portland-cement mortars.
- Label all structural members with pertinent material information.
- Provide a dedicated storage place within the building for the construction drawings and deconstruction plan.

We recommend that a future DfD credit require the preparation of a deconstruction plan. The Scottish Ecological Design Association (SEDA) has produced guidelines for such a plan (Morgan and Stevenson, 2005). The plan includes the following parts:

- A statement of strategy for DfD relating to the building.

- A list of the building elements, with expected service life and end-of-life options for each.
- Instructions on how to deconstruct the building elements.

The act of preparing a deconstruction plan will force the building designers to put systematic thought into how the building will be dismantled at the end of its life. This process could lead to creative strategies that go beyond the quantifiable prescriptive requirements that would likely be included in a future credit. As mentioned above, the deconstruction plan should be kept with the original drawings in a dedicated storage space within the building.

7. CONCLUSION

Designing for deconstruction is an act of faith; faith that new materials will become scarcer and more expensive, faith that deconstruction will become commonplace, faith that the designed building will not be burnt to the ground by fire or flattened by a tornado. Who knows what the construction industry will be like in 50 or 100 years? The authors are confident that this faith will yield rewards in the future, that deconstruction will become mainstream, and that the future owners of today's DfD buildings will look back with gratitude towards those foresightful designers who, instead of designing buildings that end their lives as a costly liabilities, designed buildings with resources that could be conveniently and profitably mined for future reuse.

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