Structural Implications of Green Roofs, Terraces, and Walls

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Abstract

As green roofs, terraces, and walls are becoming more common, structural engineers appear to be unaware of the structural issues involved and how to address them. Green roofs, terraces, and walls are an architectural/mechanical approach that tackles the sustainable design issues of storm water runoff, reduction of building energy use, and an opportunity to provide usable space to building occupants. Structural engineers must understand the structural implications of such approaches with regards to static loads, dynamic loads, serviceability, durability, and anchorage.

This document describes the structural implications of intensive green roofs/terraces, extensive green roofs, and green walls. An in depth discussion on assumed dead loads, live loads, seismic loads, wind effects, load combinations, serviceability concerns, and ASTM standards is provided. An analysis of tree loading, sloped roofs, seismic anchorage of green roofs, and recommended structural design specifications and strategies will also be presented. Lastly, strategies utilizing green roofs within the context of the sustainable metric systems such as USBGC's LEED rating system will be addressed. This document will provide a resource for engineers looking to easily, safely, and effectively facilitate the integration of green roofs into their projects.

Introduction – Awareness and Empowerment

Philosophy of Design: The key to every successful project is proper communication, pro-activeness, inter-disciplinary coordination, awareness of the project's issues, and an understanding of the design team's objectives. I.e. an integrated design approach where ignorance and passive interactions serve as barriers to efficient design. At times, uninformed approaches even eliminate design strategies that may have been feasible had the appropriate amount of time, responsibility, and research been invested into the problem. Under other circumstances, assumptions made by consultants, end in overly conservative and inefficient designs. This seems to be the current situation when design teams encounter green roofs, walls, and terraces.

Objective: As green roofs, terraces, and walls are becoming more common, structural engineers appear to be unaware of the structural issues involved, how to address them, and what questions need to be posed to the design team for proper coordination. This paper is an attempt to compile the latest information on green roofs, in order to empower structural engineers, limit their liability, add value to their designs, and make green roofs an economically viable and sustainable design feature of a project.

The following sections have been specifically tailored for the structural engineer. Several items discussed, though, will require an active and open interaction with the architect/landscape architect and/or green roof manufacturer. At times, it may even require reverse education of design team members.

Why this Paper?

This paper was pursued because of the realization of three misconceptions and misunderstandings by structural engineering colleagues. The first conservative assumption by structural engineers is to use the full saturated weight, of 110 pcf, for the full depth of the green roof assembly. Modern Green Roofs typically use lightweight engineered soils with very light drainage and insulation layers. I.e. soil does not necessarily occupy the full depth of the assembly. The second most common conservative assumption found in the industry is to assume that the green roof is a soil load rather than a dead load. Note that the use of soil load, H, in the ASCE load combinations was intended to cover lateral earth pressures. The last most common unknown is designing for tree vertical and lateral loads.

Thus two conservative assumptions could lead to over designed elements that may have depths exceeding architectural requirements. This can potentially lead to conflict and the elimination (Value Engineering) of the green roof. Thus, this paper was pursued to clarify the issues at hand, and provide additional structural engineering related data and strategies.

Green Roofs/Terraces, a Brief Overview

Overview: Green roofs are, simply, a green space created by adding growing medium and plants on top of a structure. Green Roofs and Terraces are not a new concept. Historic examples of green roofs have been documented. In modern times, the widespread use of green roofs was incorporated into designs in the late 1940s, due to land scarcity issues. The green roof movement was spearheaded by efforts in Switzerland, Germany, and Austria. Germany has emerged as the world leader in developing green roof systems and developing federal/state mandates and incentive programs. German green roof technology is migrating into the US. Since 2000, there has been a great emergence in green roof implementation in North America (Snodgrass 2006). At the present time, Chicago appears to be the American leader in green roof square footage and policy. In addition to city policies and mandates, the US Green Building Council's LEED program is expected to promote green roof installations on building structures, and in turn transform cities into sustainable habitats. See Figure 1, Figure 2, and Figure 3 for a few existing green projects.

Benefits of green Roofs: Green Roofs have an extensive documented list of benefits that include: Energy savings, building temperature control, roof membrane protection and life extension, sound insulation, fire resistance, amenity space, increased property value, reduction in urban heat island effects, storm water retention, air cleaning capabilities, ecological habitat creation, etc… Several informative texts and proceedings are available, and should be consulted, for in depth discussions of each benefit. In general, green roofs are not a single purpose building structure component, but one with numerous benefits.

Figure 1 - Chicago City Hall Intensive and Extensive Green Roof

Figure 2 - ACROS Fukuoka Office Building, Japan, with Intensive Green Roof

Figure 3 - Mountain Equipment Co-op, Toronto, Ontario, Canada - Inaccesible Green Roof

Past Failures of Green Roofs

As indicated above, green roofs are not a new concept, and have been in the US since the 1960s. Failures of green roofs from this time period have been documented. Since then, substantial progress has been made to improve the performance of green roofs. The Oakland Museum and Kaiser Center are of particular interest when it comes to past green roof failures. For additional information on both cases, Osmundson (1999) should be consulted. At the time of this paper, an extensive review of other failures was not performed. Based on preliminary literature review, it does not appear that structural failures due to green roofs are prevalent. On the other hand, there are several documented cases of green roof waterproofing and vegetation failures.

Built in the 1960s, the Oakland Museum designers were faced with numerous challenges. These challenges included 1) the fact that few green roofs had been built in the US (art rather than technical field), 2) Waterproofing techniques and performance related to green roofs was relatively unavailable, and 3) Optimally engineered soil mixes for green roofs were at an infant stage. Built-up asphaltic membranes were the standard of the time. Leaks attributed to waterproofing failures occurred. Modern green roofs advise against the use of such membranes. The soil mixes used were developed to grow plants quickly in nurseries and weren't appropriate for a green roof. Such mixes contained large amounts of organic material, which over time decayed, and in turn the soil volume decreased by 60% (Osmundson 1999). Other issues with the Oakland museum included the lack of drain slopes in planters and plugged drains.

The Kaiser center also experienced several challenges, but appears to have performed better than the Oakland Museum. The main issue identified was the decomposition of the filter fabric layer, which allowed the soil to mix with the drainage layer, resulting in clogged and blocked drains. Such situations have the potential for developing structural overload conditions such as ponding. One must note that this issue has been solved in modern times through the use of synthetic filter fabrics.

Types of Green Roofs

The FLL guideline, FM Global data sheet, and Dunnet 2008, classify green roofs into three major types: Extensive, Semi-extensive, and Intensive. Each type is associated with a specific green roof assembly and has certain load characteristics.

1. **Extensive:** The least costly of the three types of systems, extensive roofs are intended as 'ecological' roof gardens rather than amenity space. Substrate depths range between 0.8 and 6 inches. Roof vegetation typically consists of low growing herbaceous plants, such as succulents, mosses, and grasses.
2. **Semi-extensive / Simple Intensive:** Semi-extensive roofs use the same design principles as extensive green roofs, but have substrate depth ranges between 4 to 8 inches. Some documents cite 6 to 8 inches. Plant selection is increased to include grasses, shrubs, and coppices.
3. **Intensive:** The intensive green roof system essentially mimics traditional gardens at ground level. Soil media is generally greater than 8 inches. Intensive green roofs can support trees, shrubs, herbaceous planting, and lawns. Pools and water features, trees, and publicly accessible space are a typical feature of an intensive roof. I.e. terrace or plaza. Intensive green roofs require higher capital costs and maintenance.

Coordinating with the Landscape Architect's Design

Coordination with the landscape architect during the initial design stages is critical to the success of the design. The following is a list of questions that should be asked:

Questions for Dead Load Determination:

1) What type of green roof is being designed (extensive, intensive, terrace, etc…)?
2) Is the green roof sloped?
3) Is there a section of a typical green roof assembly available? What is the depth of the assembly (soil, insulation, drainage layer, etc…)? See section below.
4) What types of plantings are being planned? (This question verifies that the landscape architect has provided a reasonable soil thickness that is within typical ranges. See section below for additional Information.)
5) Will there be trees? What are the tree species, size of the trees (see discussion), and plan distribution? Are the trees bearing on the flat structure (require mounds or retaining walls), or will they require the structure to be recessed? Will the trees be confined in planters?
6) Will there be boulders, water features, art work, heavy seating structures, etc… that will impose concentrated loads? What is the layout?
7) Will there be water storage/retention on the roof or at a different location on or near the structure?
8) What future green roof layouts are possible? Should we set a criteria (ex. Mounds over 5 ft and trees over 12 kips within 10 ft of a column)?

Questions for Live Load Determination

1) Is the green roof accessible to the public? Or will it have limited access for maintenance purposes?
2) Will this terrace have vehicular traffic?

Questions for Drainage & Water Proofing Determination

1) What is the drainage plan?
2) What type of water proofing is being provided?
3) Will a leak detection system be in place?

Components of Green Roofs and Terrace Assemblies

Green Roof Assemblies are typically composed of two systems: a) Roof base assembly and b) above membrane vegetated Roof System. The Roof Base assembly includes the water proofing membrane, rigid insulation, protection board, and structural system. The typical modern vegetated roof system requires a minimum of eight (8) functional layers. The system layers include the vegetation, engineered fill, insulation, filter fabric, drainage layer, root barrier, waterproofing membrane, and structural support (See Figure 4). Each of these components (layers or courses) is described below. Under certain circumstances there are cases where layers are not required, while other situations may call for additional layers or components. The order in which these layers are assembled may also be modified. For Terrace assemblies, the plant layer is typically replaced by paving, topping slabs, rocks and boulders, and/or water features. Details provided by the landscape architect and green roof designer should be consulted.

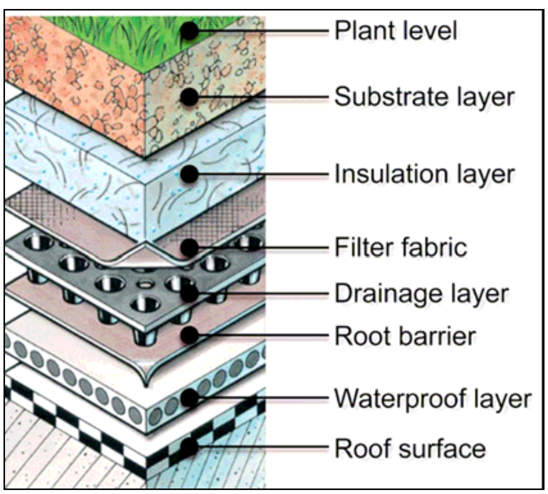

Figure 4 – Anatomy of a Typical Green Roof Assembly (http://www.obs.de/, accessed 7/4/08)

1) ***Vegetation:*** The selection of green roof plants is the purview of the landscape architect. Ground vegetation dead load varies between 2 and 4 psf. Appendix A provides additional design dead loads for various green roof types and plants. Plant selection is the purview of the landscape architect. Roof plants are selected based on their hardiness. Typically, sedums and herbs will be selected for thin roof assemblies, while thicker green roofs can accommodate larger shrubs and a wider range of plants. (See below for a discussion on tree loading)

2) ***Growing Media/Engineered Soil Layer:*** Based on the plant selection, the depth of the growing media/soil can be determined. Structural Engineers should consult the Green Plant Directories presented in Snodgrass, 2007 and Dunnet, 2008 to confirm that the soil depths specified by the landscape architect are within reasonable limits. The actual depth of the soil media will be determined by the landscape architect and/or green roof specialist based on various parameters, including climate and plant species.

   The growing media should also:
   1) Have a minimum amount of organic content to prevent settlement
   2) Have a minimum amount of silt and clay content
   3) Be lightweight
   4) Have good water storage characteristics
   5) Have suitable chemical parameters (for ideal growth)
   6) And have a good particle size distribution

   FM Global Data Sheet 35-1 2007 recommends that standard landscaping soil or loam should not be substituted for green roof media. Landscaping and nursery soil is engineered differently than a green roof soil, and thus should be avoided. The FLL guideline also provides gradation and performance requirements for engineered soils.

3) ***Insulation Layer:*** The insulation layer is either installed above or below the waterproofing membrane. When installed below, the system is referred to as an inverted roof membrane assembly (IRMA). An inverted membrane system takes advantage of the insulation layer to protect the waterproofing membrane from puncture and UV degradation. Rigid insulation board must also have sufficient compressive strength for the load being supported. Even though a green roof can serve as an insulating layer, it has been recognized that climates having extended periods of winter will still require an insulation layer.

4) ***Filter/Separation Fabric Layer:*** In order to maintain the drainage and water storage capabilities of the drainage layer, a non-clogging synthetic filter fabric must be installed. I.e. non-biodegradable. The filter fabric must be constructed of a structure that resists clogging from fine soil particles (silts and clays). Typically this filter fabric is only about 1/8 inch thick.

5) ***Water Storing Drainage Layer:*** The drainage layer typically has two competing characteristics: 1) Drainage of water from the plant root zone and 2) storage of water to provide plants with moisture during periods of

dryness. There are three main types of drainage layers: Drainage plates, Granular media, and Drainage Mats. For additional information and construction details, the "Green Roof Handbook," published by Resource Conservation Technology, is a great resource.

Drainage Plates are typically waffled rigid thermoplastics (polyethylene or polystyrene) that are easy to install and are available in a variety of sizes, depending on the type of green roof. See Figure 5 and Figure 6. The drainage plate system is typically 1 inch to 2-½ inches tall. When concentrated loads are imposed on the drainage plate, such as trees, the drainage plate manufacturer should evaluate its load bearing capacity. Under certain circumstances, the drainage plate can be reinforced or filled with granular material to provide additional load bearing capacity.

Granular Media systems are composed of a base layer of lightweight, inorganic, granular media. This granular media will typically contain porous light weight aggregate. Embedded within the granular media are several drainage conduits. Granular media systems are typically 2 to 6 inches thick, depending on the type of green roof. See Figure 6.

Of the three systems available, the drainage mat system is the thinnest, lightest, and fastest to install system. This type of systems is composed of a multi-fabric mat that combines soil separation, drainage, and protection functions. Its one drawback, though, is its limited water storage and drainage capacity. Typical drainage mat thicknesses are in the range of 3/8 inches. See Figure 6.

6) ***Protection Fabric:*** The protection fabric is typically placed above the water proofing and root barrier membrane. This layer's role is to prevent damage during construction and roof maintenance activities. Fabric weighs between 15 and 25 ounces per square yard, with a nominal thickness of ¼ inch. Protection fabrics can also be designed to have water storage and capillary capabilities. In older designs, concrete topping slabs were also used as a protection layer (Osmundson 1999)

7) ***Root Protection Barrier:*** Certain water proofing membranes, such as bituminous or asphalt based products, are not resistant to root penetration or degradation due to micro-organisms, and thus require a root protection barrier. Root barriers are usually composed of PVC and sometimes contain release agents. Typical thicknesses range between 0.03 to 0.04 inches.

8) ***Waterproof Layer:*** For long lasting and maintenance free life, green roof waterproofing selection is critical. Water proofing membranes should be elastic, must withstand ponded water, be non-biodegradable, and resistant to root penetration. Water proofing membranes can be: fluid-applied asphalt based, torched applied bitumen, thermoplastic single ply, or thermoset polymer-based single-ply. Due to reduction in temperature fluctuations, European studies have indicated that placing soil and plant media over a water proofing membrane can double the membrane's life span when compared to a conventional roof (Peck NA). Thicknesses and weights vary.

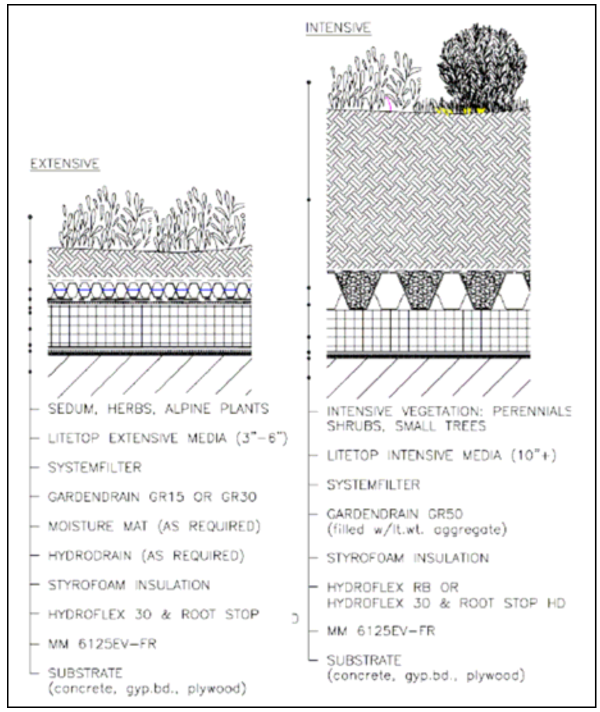

Figure 5 – Hydrotech Typical Standard Intensive and Extensive Green Roof Assemblies (http://www.hydrotechusa.com, accessed 7/4/08)

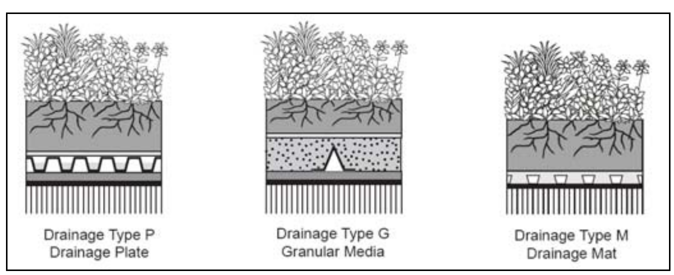

Figure 6 - Drainage Layer Systems (Resource Conservation Technology 2006)

Design Loads, Combinations, ASTM Standards, and Structural Checks

Design Loads: The following is a brief discussion of the various loads applicable to green roofs that structural engineers must consider. The FLL "2002 Guideline for the Planning, Execution and Upkeep of Green-Roof Sites," and the 2007 FM Global "Property Loss Prevention Data Sheet 1-35 – Green Roof Systems," provide the most comprehensive discussion to date on structural engineering related design items for green roofs.

1. **Dead Loads:** As discussed above, the landscape architect has a variety of green roofs assemblies to choose from. Appendix A provides various design load references. Chapter 13 of the FLL Guideline provides additional reference design load and geometric data for materials used in drainage and vegetation support courses. A 15 percent increase in the specified depth is recommended to account for future additions of growth media (FM Global 2007).
2. **Live Loads:** Should be determined based on the type of occupancy and local building code requirements. FM Global recommends that extensive green roofs be designed for no less than 12 psf when considering live load reduction, and a minimum of 20 psf for intensive and simple intensive green roofs.
3. **Transient Live Loads:** Per ASTM E 2397, transient live loads are the weight of transient water contained in granular drainage materials and geocomposite drain layers. This load is treated as a live load in the building code load combinations.
4. **Snow and Rain Loads:** Should be based on the local jurisdiction's building code requirements.
5. **Wind Loads:** Several performance requirements related to wind uplift of membranes, soil media, wind-borne debris, and building height restrictions are discussed in FM Global Data Sheet 35-1. Roofs should be designed for the envelope of wind uplift on a 1) bare roof and 2) saturated green roof.
6. **Seismic Loads:** Current recommendations appear to indicate that the full saturated dead load of the green roof structure shall be used as part of the seismic mass. Transient live load is not included in this mass calculation.

Load Combinations: Building structures should be verified for two building conditions: 1) Building Structure with bare roof (conventional roof) and 2) Building Structure with saturated green roof. I.e. essentially doubling the number of load combinations that include the dead load component. This design strategy essentially envelopes the design of the building structure under maximum/minimum base shear and overturning conditions.

ASTM Standards and FLL Tests: The two ASTM standards related to green roofs are ASTM E 2397, "Standard Practice for Determination of Dead Loads and Live Loads Associated with Green Roof Systems," and ASTM E 2399, "Standard Test Method for Maximum Media density for Dead Load Analysis of Green Roof Systems." FM Global 35-1 indicates that if green roof assemblies are not tested per ASTM E2397 and E2399 then the design load should be based on a saturated density not less than 100 pcf.

The FLL Guideline should also be consulted for testing requirements related density, water retention, water permeability, and root penetration resistance determination.

Miscellaneous Structural Checks related to Green Roofs:

1) Seismic mass irregularities shall be verified for the bare roof and fully saturated roof condition.
2) Gravity beams, seismic drags/collectors, and connections supporting green roofs need to be carefully evaluated for high bending combined with axial loads
3) Punching Shear of concrete slabs shall be carefully evaluated
4) Formation of expected plastic hinging mechanisms in lateral systems should be carefully evaluated.
5) Construction sequencing of brace and shear wall installation, to prevent dead loading should be considered.

Contract Documents: Load Maps, Submittals, Details, Specifications, and General Notes

The best way to communicate your basic design assumptions is to create load maps, indicate the design loads on the contract documents, or provide a performance specification of the weight characteristics of the green roof. This will require appropriate coordination with the landscape architect. By properly specifying and coordinating reasonable design criteria, several green roof manufacturers can bid the job. The landscape architect, though, maintains control over the required soil thicknesses and green roof components appropriate to the plant selection and hardiness requirements.

General Notes: As part of the general notes, it is recommended that the contractor provide submittals of the selected engineered fill (density and permeability), and the waterproofing/green roof assemblies to the structural engineer for structural impact review. It is also good measure to request a mockup of the final selected assembly be constructed and tested according to ASTM E 2397, "Determination of Dead and Live Loads associated with Green Roof Systems" and ASTM E 2399, "Standard Test

Method for Maximum Media Density for Dead Load Analysis of Green Roof Systems." Although, these standards will usually be indicated in the landscape architect's specifications, it is highly recommended that a dedicated general notes section be provided on the contract documents. Appendix B provides a sample general notes section that should be modified for the particular project.

Details & Sections: For additional clarification, a typical section of the assumed assembly should be provided in the structural design documents. Details are the best way to communicate to the design team during the design process what the basic weight and geometric assumptions of the green roof assembly are.

Load Maps: Load maps are probably the clearest way to indicate structural loading limits and design criteria. These maps can be used as a coordination tool as well as a documentation tool for future structural plan review. It must be understood that green roofs can change over time. Designing for flexibility is an item that should be addressed in the design phase. I.e. not mimicking the actual design, but adding value to the structure by enveloping various scenarios through a load map. For example, a load map could indicate that all mounds over 5 foot and trees over 12 kip shall be placed within 10 ft of a column.

Specifications: Specifications are a key resource of design information. Green roof specifications will typically be provided in CSI Division 7 "Thermal and Moisture Protection." Green roof specifications usually include all materials, testing, installation, and inspection procedures. Under the materials section, the soil properties should be listed. Of these properties, the structural engineer should be aware of and confirm the soil density (saturated and dry density) provided in the specification. Hardscape features and paving materials can also be included in such specifications. Manufacturers of green roof, terrace, and plaza assemblies will usually have specifications available for review and modification. These specifications are a good starting point when reviewing and determining the design criteria with the landscape architect.

Special Case: Mounds

Mounds can be used as a landscape feature alone, or can be used to create a transition between a low planted area and the base of tree. There are several methods to creating mounds using strategies that keep the superimposed dead load to a minimum. Some of these strategies include

1) Creating void spaces using "lost" form-work,
2) Using polystyrene blocks below the growing media,
3) Using lightweight aggregate fill beneath the growing media,
4) Or molding the structural system.

Each method should be evaluated based on constructability, sequencing, loading, flexibility in design, and cost. Molding the structural system appears to be the most expensive and least flexible of all the alternatives available.

The California Academy of Sciences, in San Francisco, is one particularly interesting project that molded the 2.5 acre structural roof system to create seven mounds, with slopes as steep as 55 degrees. Curved roof steel beams not only formed these hills, but were also expressed as an exposed ceiling. (See Figure 7). To prevent erosion, a framework of criss-crossing gabions (an epoxy coated wire cage containing lightweight volcanic rock) was installed over mound areas. In between gabions, modular planting trays were easily installed.

Figure 7 - California Academy of Sciences (www.wired.com, accessed 7/4/08)

Special Case: Designing for Trees

One of the most challenging aspects of green roofs is the determination of loads imposed by trees. At times, basic information about the weight and geometry of a tree can be difficult to obtain from a landscape architect or nursery. There are simple questions an engineer should pose to a landscape architect in order to extrapolate structural design parameters. The basic parameters that should be requested are:

1. Tree Species and Shape (see below for discussion),
2. Trunk size (caliper) and height of Tree to be planted; Final estimated size and height. (Usually box size or Root ball is also a common specification)
3. Whether the tree root structure will be confined (planter) or unconfined.
4. Are the trees container grown or field grown?

Once these parameters have been determined, an engineer is able to estimate the total dead load, estimate the wind loading imposed by a tree, and the root structure behavior.

ANSI Z60.1 "American Standard For Nursery Stock," published by the American Nursery & landscape Association is a useful document that should be consulted to understand the landscape architect's specifications. ANSI Z60.1 provides information on height-diameter relationships for various species groups as well as container, box, and root ball size.

Based on the information provided by the landscape architect, there are two general routes that should be pursued. The first route is to communicate with the local nursery. The second route for determining tree weight and geometry is through forestry information. Foresters have developed several algorithms to estimate physical parameters of several tree species. Physical parameters may include volume, weight, height to diameter ratios, crown width, leaf area, etc…(Schlaegel 1984, Clark 1990, Temesgen 2007, Peper 2001). The algorithms are typically based on a data set where regression analysis was performed to obtain an easily calculable equation. Even though there may be some error in the regression analysis, such methods provide an insight to the order of magnitude of the parameter sought.

Tree Dead Loads: The dead load of a tree includes the green weight of the root ball, trunk, and tree canopy. Several resources and documents are available for estimating the weight of a tree.

Communicating with the landscape architect and/or the local nursery should be the first route pursued. Some nurseries will provide tree weights based on box/ball size and species. Based on regional differences, nurseries may have different weights for the same species and box size. Some nurseries are not keen on providing preliminary weight data due to liability concerns. Older nursery catalogues sometimes contain weight information. If information is wanting, table A-4 (Appendix A), can be used for preliminary design estimates. As can be seen from Table A-4, there can be substantial differences between container and field grown trees. Verifying the landscape architect's specifications for container or field grown items is required. Once a project is under construction, though, trees selected from the nursery can be individually weighed.

In the second route, algorithms developed by foresters to estimate the dead load of a tree can be used (Schlaegel 1984, Clark 1990). A small sample set of algorithms has been provided in Appendix A. Some algorithms estimate weight of the above ground portion. To determine the root weight, it is suggested that 20% of the above ground weight be used (Schlaegel 1984).

One item that must be recognized is that the estimated weights are typically for trees culled in a forest environment, rather than grown in a controlled environment such as a nursery. Data on trees grown in an urban setting on sidewalks and streets is also available (Peper, 2001). Data and algorithms for nursery grown trees do not appear to be available at the time of this paper.

Once the dead load of the tree has been estimated, two basic dead load cases should be checked. 1) The point load imposed by the tree during installation, concentrated over the projected area of the root ball/plate and 2) The point load of the maximum expected weight of the tree during its life time over a slightly larger projected root area (unless restricted by a planter or pot). It is not clear whether arboriculturalists have determined what the effective bearing area of the root plate is, once its root system has been established (See discussion below on root plate estimates). The manufacturer of the drainage layer should verify the load carrying capacity of the green roof system for such point loads.

Wind Loading and Trees: Wind induced moments, caused by trees, imposed on structural support systems have been known to cause serviceability failures. Thus, it is important for the structural designer to be aware of such conditions and consider this load case for design.

The general behavior of trees under wind loading is to naturally reduce their surface area, through rotation of its leafy parts, elastic bending and sway of its branches, and energy loss within the wood and root/soil system. In an urban setting, trees may experience more wind loading action than trees in a forest, which take advantage of the protection provided by their neighbors. Trees confined and protected by building structures will also be subjected to less wind loading. An interesting paper on tree damage and behavior during hurricanes discusses correlations between pre-storm tree conditions to branch resistance, strength, defoliation, and crown loss (Francis 2000).

In the paper "Dynamic Loading of Trees," Ken James (2003) describes three damping systems a tree employs to reduce forces on the main tree trunk: hydraulic damping, mass damping, and viscoelastic damping. Hydraulic damping is attributed to aerodynamic drag forces of the foliage in the wind. Mass damping is provided by the interaction of the side branches attached to the main limb. Viscoelastic damping is provided by tree's stem and root system. Although, dynamic response and stress analysis of tree structures have been performed, simple static approaches to estimating base reactions are available, but wanting.

Even though, there is extensive research available on the wind loading and failure of trees, there does not appear to be a consensus amongst tree specialists and arboriculturalists on how to estimate wind loading of trees. Simple static approaches based on “bill board” type structures having porosity have been used (James, 2003; Sterken, 2005; Coder, 2000). Even though simple, some arboriculturalists are of the opinion that the overturning moments calculated by this method are significantly overestimated (James 2003). Sterken (2005) on the other hand indicated that dynamic wind loads can excite resonant motion, generating dynamic responses that can be far larger than what equivalent static loads would indicate.

In the paper “Estimating Wind Forces on Tree Crowns” by Dr. Coder (2000), a simple table is provided to convert a wind speed exposure to an applied projected surface area loading. In this case, the crown density, a measure of velocity drop across the crown, is used as a wind drag factor. Once this pressure has been determined, the appropriate surface area of the crown shape should be selected based on the tree species. “Crown Shape Factors & Volumes” (Coder 2000) provides guidance on shapes varying from cylinders to parabaloids to thin neiloids. Wind loading on the stem, below the crown, can easily estimated using approaches similar to pole analysis. With this information, the reaction overturning moment can be determined.

Sterken (2005), on the other hand, uses a code based approach taken from EuroCode 1 to estimate the force imposed by wind loading on a tree crown. In this method, though, engineering judgment must be used when determining the aerodynamic coefficient. The aerodynamic coefficient describes the flexibility that the tree uses to reduce wind demands. For a Eucalyptus camldulensis a drag coefficient of 0.25 is recommended. Sterken (2007) studied the stability of palms as well, but did not publish an estimated drag coefficient. The calculation of the wind exposed area for this method can either be estimated or calculated using specialized software (Sterken, 2005; Niklas 2002). Since drag coefficients do not appear to be readily available, engineering judgment should be used when using this method.

One last note on the exposed area that all engineers should be aware of is the design of trees in winter climates. Wind pressures on trees coated with ice can double or triple the wind force on a tree (Coder 2007). Snow and ice dead loading should also be accounted for.

Other factors that play into the wind loading equation is pruning. Crowns can be reduced in height and extent; raised above the ground; or thinned (Coder, Sept 2000). Such methods will reduce wind forces and can be effectively used to limit the size and weight of trees.

Now that the wind overturning moment has been estimated, what resists the load? The root structure of a tree serves to resist wind lateral loads. For the typical tree, the root plate radii are approximately nine (9) percent of the total tree height. The root plate can vary between two (2) and twenty (20) percent of the total tree height (Coder, 2000). This data, of course, has its limitations to trees that have root systems that are laterally extensive but shallow. Some tree species use a combination of deep bayonet-like roots and lateral roots (Niklas, 2002). These deep bayonet roots effectively acts as a laterally loaded pile. It is uncertain whether trees having deep root structures would be able to adjust and resist wind loads in a green roof setting. It has been documented, though, that the geometry of the root structure changes and adapts in proportion to the loads transmitted by the trunks (Niklas, 2002).

Tree Roots: Although green roofs have root barriers as part of the green roof assembly, root behavior and control cannot be disregarded and must still be understood. Roots pose a direct threat to a roof structure’s structural and water-tight integrity. (The following concepts and strategies also apply to vegetation other than trees).

As indicated above, the root structure of a tree provides the vertical and lateral resistance of a tree system. A tree will tend to expand its root and trunk system in response to available resources and structural loading. The root tips are able to generate force through the expansion of tissues in new spaces. Several arboricultural resources indicate that roots can only take advantage of cracks and faults already in materials (Coder 1998). Once a root tip enters a pore space, it expands the pore space, progressively elongates the space, until resources are consumed, or the penetration resistance of the material is greater than the pressure that can be developed by the root tip. Such growth characteristics should be controlled in a green roof and terrace environment.

There are eight primary strategies to control root growth in a free field or urban environment (Coder, 1998). These processes are based upon limiting root, adjusting/controlling resource availability, and using soil attributes. The eight strategies are: Intelligent development, Kill zones, Exclusion zones, Air Gaps, Barriers, Directed Growth, Species Selection, and Avoidance. These strategies alter resource availability/volume (water and oxygen) and redirect or destroy the root system.

The Exclusion zone strategy prevents root growth by modifying the surrounding soils physical (compaction), or chemical composition. Compaction of soil around a tree tends to decrease the pore space, limits water permeability, and oxygen through the soil (Coder 1998). Use of slurry and clays are also effective, but this strategy should be avoided in the green roof setting.

The air gaps strategy is an attempt to create large air gaps having poor water holding capacity that dries out the space and prevents root growth. Providing a stone drainage matrix around a tree is one method to achieve the air gap strategy.

The Barriers strategy includes traps, deflectors, and inhibitors. Traps allow root tip growth through the material, but constrict and strangle radial root growth. Solid pieces of plastic, wood, and metals can be used as deflectors to reorient and prevent root growth in a certain direction. An inhibitor barrier uses chemical herbicides to inhibit root tip growth. Some disadvantages to inhibitor barriers, are that they have a limited life span, are prone to damage by the structural action of the roots on the fabric, as well as the possibility of roots pushing thin zones (Coder 1998). Containerization is also a barrier strategy that should not be excluded from consideration (Osmundson 1999).

The Directed Growth strategy essentially directs root growth by providing healthy resources in one area and poorer resources near infrastructure. Use of culverts, raceways and trenches can also lead roots away from infrastructure (Coder 1998).

In "Methods for Root Control," Coder provides several tables under the Species selection discussion that provides estimates of the structural rooting distance and critical rooting distance. These estimates can be used to offset trees from infrastructure in order to minimize damage. These tables are only typical estimates. Species specific guidelines should be consulted. These tables could potentially be used in determining root plate size for distributing the laterally induced wind moments and vertical dead load of a tree.

Of these strategies, several are applicable to green roofs and should be considered in the design and detailing by the landscape architect and green roof installer. It would be diligent of the structural engineer to pose the question of root growth control to the design team. For additional information, the "Tree Root Growth Control Series" compiled by Dr Coder provides a wealth of specific strategies for the landscape architect.

Temporary Tree Bracing: During the initial stages of planting a tree, wind throw is an issue. To prevent trees from tipping over, prior to establishment of its root structure for support, trees are braced or anchored in some manner. Bracing techniques available are: collar bracing, box bracing, and root ball anchorage. Collar bracing/guying, with concrete dead men, can use cables or lumber stakes to provide tree latter support. This bracing is usually visually obtrusive and can pose a safety hazard. Box bracing uses underground wooden braces nailed to the tree box that are able to rot away as the root plate establishes itself. Root ball tie downs and cabling can also be concealed beneath the surface and has the ability to improve a tree's resistance to toppling (Coder, 2000a). Root ball anchorage is usually anchored deep into the soil or into the structure itself.

***Permanent Tree Bracing*:** There are several manufacturers of permanent cable-spring and bracing systems. The main intent of such systems is to prevent excessive tree leaning, which may ultimately lead to instability and toppling (Coder 2000a). Bracing also helps to limit the impact force of the tree as it strikes the ground or adjacent structure. "An engineering Study of Tree Cables" by Ken James can provide additional information for the curious.

Special Case: Sloped Roofs

Sloped roofs perform and behave differently from flat and low sloped roofs. Moderately sloped (3:12 to 5:12) and steeply pitched (5:12 to 12:12) roofs require special attention from the landscape architect and engineer. The water holding characteristics of the green roof vary along the slope, with most of the water accumulated along the lower edge. I.e. Dry conditions near the top edge and moist, oxygen deprived conditions near the lower edge. Plant selection, drainage strategies, maintenance (due to loss of nutrition), and irrigation systems to achieve a balanced sloped based green roof are design elements that must be considered (Snodgrass 2006). For the structural engineer close attention to the drainage patterns and areas of water accumulation in order to avoid ponding should be considered.

Two additional structural requirements related to green roofs is related to green roof slope stability and anchorage under static and dynamic loads. Under static load it is recommended that slopes steeper than 2:12 should incorporate slope stabilization measures to prevent slipping and slumping (Dunnet 2008, COLA 2006, FM Global 2007). Slope stabilization is provided by structural anti-shear stability layers or anchorage. The maximum possible slope is limited by the smallest coefficient of friction between the various membrane and fabric interfaces within the green roof assembly. In "Green Roofs and Living Walls," Nigel Dunnet indicates that the use of strapping, laths, battens (underneath waterproofing), or grids can be readily used for roof slopes up to 7:12. The FM Global Property Loss Prevention Data Sheet 1-35 2007 recommends against roof slopes greater than 40%. The FLL Guideline provides additional information, requirements, and execution for protection against slipping and shearing.

There are several products on the market for anchoring slopes under sustained static loads. Some products include a tension cable system attached to a cellular confinement grid that provides free drainage as well as slope restraint. FM Global Data Sheet 1-35 2007 also indicates that the shear/sliding loads induced by a slope should not damage any underlying layers. One recommended method indicated by the FM Global data sheet to increase the shear resistance of the growth media is to add crushed aggregate to the soil, limit fine aggregate, allow good root penetration, and limit washout and erosion.

Beyond 7:12, specialized devices and engineered media must be used to stabilize the static green roof loads. Certain manufacturers have developed green wall systems that can be adapted for green roofs (GLT 2008). Typically these systems call for a modular construction approach.

Based on the research performed for this paper, it is unclear whether the slope limitations indicated by several authors were also applicable for dynamic lateral loads. Similar to flat roofs, the design lateral load to be used for anchorage design is unclear. It is also unclear how seismic slope stabilization analysis of a sloped green roof is performed. Additional research needs to be performed by green roof manufacturers in this area. Use your engineering judgment until research is available.

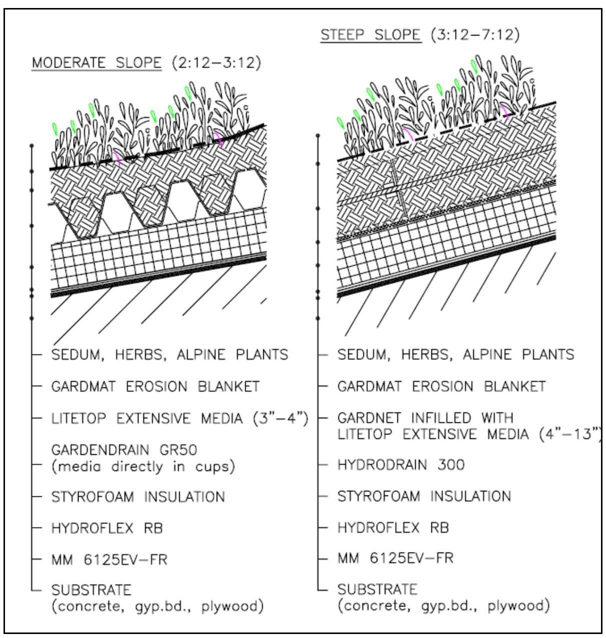

Figure 8 – Hydrotech Typical Standard Sloped Green Roof Assemblies (http://www.hydrotechusa.com, accessed 7/4/08)

Special Case: Pavings, Boulders, and Water Features

As part of an intensive green roof program, hardscape features such as pavings, boulders, water features, and artwork can be incorporated into design. Such components convert a roof space into an amenity space. Each element should be evaluated for its imposed loading on the structure. Boulders and heavy art works can pose a particular challenge.

When thinking about storm water management, specialized pavers can be incorporated. Pervious concrete pavers can simultaneously provide interesting texture and drainage capabilities. PCA and ACI should be consulted for additional information on pervious concrete surfaces. For vehicle accessible terraces, engineered grass pavers can be also be included. Manufacturers specializing in engineered grass pavers should be consulted for weight and drainage capabilities.

Special Topic: Blue Roofs

Blue roofs are essentially urban beaches that may provide rooftop water play areas, eco showers, misting sprays, water sculptures, etc…Water runoff from blue roofs can be used to irrigate green roofs and cool the roof structure. Blue roofs make efficient use of roof space in a city. Like a green roof, the structural impact of such programming should be assessed. One structural approach that could be incorporated into the blue roof, as part of the structural system, is a tuned liquid damper (TLD).

Serviceability Considerations

Deflection: The deflection serviceability criteria of a green roof should be no different than any other roof. Some items to consider when selecting the appropriate deflection criteria are: whether waterproofing membranes can be damaged by deflection and ponding. When designing for a semi-intensive or intensive green roof it is also prudent to review the sequencing of the superimposed load. Large loads imposed by intensive roofs may require cambering, preloading, or sequential loading of the structure. Long term deflection criteria should also be carefully reviewed and the structural system appropriately designed. For one and two way concrete slab systems, bays adjacent to the perimeter will tend to deflect more due to moment discontinuity at the edge of the structure. This case can usually be solved by designing and detailing walls below the slab to accommodate an additional moment. One other solution is to incorporate the parapet wall, a green roof retaining wall, as an upturned girder.

Waterproofing, Drainage, and Leak Monitoring: One of the key components of a green roof system that must be maintained, monitored, and installed correctly is the waterproofing membrane and drainage system. Usually, such systems are not under the purview of the structural engineer, but the SEOR should be aware of the issues in order to limit liability. Several different types of membranes are available (See previous discussion). Some membranes are more prone to degradation than others. Several different drainage layer systems are also available, each with their own issues. Since leaks are difficult to detect, locate, and expensive to repair in a conventional green roof system, owners have the choice to install electric field vector mapping (EFVM). EVFM uses water as an electrical conductor that establishes a circuit once water contacts the structural support system. EVFMs used with modular systems appear to be the easiest to remove in order to repair damaged areas. Other methods for leak detection include creating water proofing "zones" or panels where water is contained within an area beneath the waterproofing membrane. Such techniques allow repairs to be made in an isolated region. Each waterproofing manufacturer has specialized systems designed for green roof applications.

Retrofit of Existing Structures

Retrofitting existing roof structures for installation of a green roof is an absolute possibility. Under certain conditions, the existing structure need not be retrofitted. One of these conditions is where the roof ballast is removed and replaced with an extensive green roof having the same superimposed dead load and live load criteria (COLA 2006, Snodgrass 2006). For this sort of approach a careful review of the modified drainage plans and water proofing should be considered. One item for the landscape architect to note is that plant selection is limited in the ballast replacement strategy.

Additional strengthening of the roof structure to accommodate larger depths of green roofs is also possible. Basic structural strengthening techniques can be used. One item to note when verifying new green roofs is that a transient live load must be considered as part of the structural engineering load combinations.

As with new roofs, whenever the retrofit of an existing roof is being performed, additional considerations related to plant survivability, drainage, and fire safety provisions must be coordinated. It is recommended that a non-vegetated perimeter around the edges of the roof, skylights, roof hatches, and drains be provided (COLA 2006). A non-vegetated perimeter should also be provided around existing mechanical equipment and exhaust structures in order to prevent the possibility of fire initiation of plant structures and to prevent scorching (plant stress and mortality) of the green roof plants due to the heat produced by these elements (Snodgrass 2006). High velocity exhaust by HVAC units can also cause plant damage (FM Global 2007). Relocation of rooftop mechanical equipment is a possibility.

Green Walls, Living Structures, and Surfaces

One other "living" strategy that can add value to a structure is the use of green walls. As will be discussed in the synergies section of the paper, the use of green roofs to reduce energy requirements is limited by the ratio of the roof surface area to the total building surface area. Well designed green walls compliment the benefits reaped by the use of greens roofs. In Europe and Asia there are claims that green walls are considered more valuable than green roofs (Sharp 2007). Benefits of green walls include reduction of building temperature (shading, insulation, evapotranspiration), dust reduction, pollution containment, reduction in storm water volume flow rate, increased bio-diversity, noise reduction, and used for ornamental purposes. Green walls are not limited to building structures, but can be added to site walls, structures, and surfaces. Awareness of the implications of a green wall strategy from a structural perspective needs to be understood. Even though green wall practice isn't a new strategy, it is documented that façade greening is a relatively new discipline (Dunnet 2008). It also appears that information on structural loading of green walls is wanting. Thus, items and issues a structural engineer should consider will be presented. Additional research regarding the structural loading imposed by green walls will need to be performed.

Green walls can be grouped into two types: Green Facades and Living Walls.

Green Building Walls/Façade Greening: In the context of buildings, green walls can also be referred to as façade greening. Because green walls are living, façade greening is a self-regenerating cladding system for buildings that changes shape and structure over time. Thus, the possibilities that structural loading can change over time, as well as issues related to durability, are present.

Green façades are composed of climbing or cascading plants that are rooted at the base of a structure, an intermediate planter, or on a rooftop. Traditional green walls used self-clinging climbers, but modern green wall systems prefer to use a network of cable-ropes or a trellis, offset from the building façade system. Trellis systems can either be attached to the building structure or are free standing (Sharp 2007, Dunnet 2008). Examples of plants requiring support structures include twining vines, leaf stem climbers, and scrambling plants.

Self-clinging wall climbers require no additional structural support and either use a root or an adhesive sucker to attach themselves to the façade. Root hair attachments will typically penetrate cracks and gaps of rough surfaces. To prevent deep root penetration, root clingers should not be used on walls having soft mortar and tiling (Dunnet 2008). Climbers using adhesive suckers are less likely to cause damage than root clinging climbers. Surface damage attributed to adhesive climbers can usually be attributed to improper removal. In all cases, one should avoid greening historic buildings with self-clinging green walls. Damage can include marks left by pulled suckers and/or aerial roots.

Twining climbers require a vertical support structure for growth and load support. Their weight can become considerable over time due to formation of tree-like trunks and branches. Large twining climbers also have the ability to twist their supporting structure with the result of anchorage failure (Dunnet 2008). Anchorage issues can be solved through the use of overload clamps and extra length of cable. Tendril and leaf twining climbers attach themselves to the vertical load carrying support system through tendrils. Usually the trellis support system for these types of plants is made of equidistant horizontal and vertical supports. Ramblers and scramblers typically use their thorns as a means of attachment. Usually, ramblers grow better in horizontal direction.

Seventy eight (78) feet appears to be the maximum height a green wall can attain (Dunnet 2008). To extend beyond this height, intermediate planter levels can be installed up the building.

The factors affecting the choice of the green wall support system are: Climbing mechanism, plant size, local climatic conditions, and architectural design factors. Of these, climatic conditions and plant size have particular structural implications. Plant weight is related to the type of climber, species, and regional growth conditions. Plant weights can vary between 2 and 110 psf of wall area (Dunnet 2008). The additional weight of rain water and dew should be considered. When snow fall is a possibility, the weight of snow should be accounted for. For snow and rain, the load recommendation is two times the plant weight for deciduous plants, and three times the plant weight for evergreens. Where trellis systems are offset from the building façade, the potential for increased façade axial load and moment, beyond typically loaded facades, is apparent.

In terms of wind loading, shallow profile climbers impose a much smaller load than climbers having leaves and branches. Maintenance to remove extended growth appears to be the key to preventing overloading due to plant extensions. As far as surface roughness effects of green walls are concerned, it is unclear whether building code recommendations cover this case.

Trellis systems used to support green walls vary. Based on the trellis system selected the load can either be imposed on the building structure or through the trellis system itself. Four varieties include 1) direct wall fixing, 2) hanging system (roof), 3) Standing or rigid rod with foundation, and 4) Steel cabling and tensioned system (Dunnet 2008). Variations of these systems are available.

Durability, structural support, placement, and maintenance of the green façade wall should be assessed in the design process. Damage to the building structure and failure of the trellis support structures have been documented and can be attributed to a variety of reasons. The reasons appear to be related to insufficient strength and anchorage of the trellis system to the structure as well as structural overloading due to plant growth and other environmental loads. "Fassaden- und Dachbegrünung by Brandwein and Köhler (1993) should be consulted for additional details.

Living Walls, Structures, and Surfaces: Living walls are also known as biowalls, "muir" vegetal, or vertical gardens. This is also known as "eco-technology." Such living systems are usually composed of modular pre-vegetated panels or fabric systems that are either anchored to a structural support system and/or held away from the structure. One other form of living walls is the integration of plants into engineered structures such as retaining walls, slope stabilization, or bank protection of streams and rivers. This second living wall category is usually referred to as bioengineering. Bioengineering can be an effective strategy that replaces civil engineering strategies that incorporate concrete and other heavily engineered systems.

In the living wall system, product manufacturers should be specifically consulted for modular panel and fabric mat weights. Modular, gabion, mortared, and cast-in-place retaining walls have great potential and can be planted to serve as green walls. Attention to durability issues as well as consideration of plant root behavior should be considered. Manufacturers of modular walls should be consulted for additional information on their green wall systems. A maintenance program to keep plant growth under control should also be incorporated. For additional discussions on green civil engineering walls, Dunnet (2008) should be consulted.

Specifications and General Notes: Similar to green roofs, green walls will also require quantitative performance data. Specifications will typically be controlled by the Green Wall designer. It is advised that structural general notes be included in the contract documents. Appendix B provides a sample general notes section for green walls.

Special Topic: Green Roof & Wall Synergies

The advantages of using Green roofs were presented in a previous section. Some specific strategies taking advantage of characteristics of the green roof system are presented below. The topics are by no means the only synergies where a green roof can be incorporated.

Solar Panels and Green Roofs: Probably one of the greatest synergistic combinations of sustainable strategies is the incorporation of a green roof structure with solar panels. German research has indicated that solar panels perform optimally at temperatures under 77°F (Earth Pledge 2005). Green roofs have the ability to cool the surrounding area, and thus can assist in increasing the performance of photovoltaics. Structural verification, detailing, and coordination of both elements should be performed.

Several projects have been constructed using this combined strategy. The Primary and Secondary school in Unterensingen, Germany incorporates a 3 inch, 15000 sf green roof. Because of solar incentives provided by Germany, for renewable energy, it was estimated that it would take 10 years for the photovoltaic panels to payback the entire roof system. Not only will it pay back itself, but this component of the school doubles as a student laboratory and is used as part of the school's science curriculum (See Figure 9).

Figure 9 - Unterensingen, Germany; Primary and Secondary School extensive green roof with photovoltaics (www.greenroofs.com/projects, accessed 7/4/08)

Water Storage, Storm Water management and Green Roofs: There are several studies and papers related to the use of Green Roofs as a storm water management tool. Some jurisdictions may provide incentives to reduce water and sewerage charges. Such incentives are aimed at reducing the amount of infrastructure required to transport storm water and help control the rate and quantity of storm water flow. Controlling the rate and quantity of storm water prevents the overload of public utilities and potential release of contaminated water into the ecosystem. Berlin, Germany and Portland, Oregon have seen the benefits of increasing the use of green roofs as storm water management tools (COLA 2006).

In "Ecoroof Questions and Answers", The City of Portland Bureau of Environmental Services, indicated that green roofs capture and evaporate between 10% and 100% of precipitation incident on the roof. Several different studies indicate different retention and release rates. In almost all cases the storm water that isn't retained by the green roof can be stored as grey water. This grey water can be used to flush unrinals and provide irrigation water for ground level plants or the green roof itself. Incorporating storage structures such as tanks into the structural system should be considered. Storage tanks can be located at the roof level or in the foundation system. When stored on the roof, the pumping requirements are reduced, but the structural system required to support it becomes more extensive. When storage systems are incorporated into the foundation system, additional coordination with the foundation and the use of larger pumping systems are required. One other strategy to consider when incorporating storage systems is the possibility of integrating it with a mechanical system. I.e. Pre-cool intakes using the thermal mass of the water.

Integrating Green Roofs and Walls with Mechanical Systems, Increased Energy Performance, and Temperature Control:

Green Roofs provide an owner and community with numerous benefits. However, economics tend to drive an owner's decision of whether to install a green roof or not. Based on studies, one can argue the benefit green roofs have on reducing heating and air-conditioning costs over the life of an individual building. There are several considerations, though, that must be taken into account to substantiate this claim. Plant selection (evergreen), depth of soil, moisture, climate, and seasonal aspects appear to be the major variables related to energy performance and temperature control (Dunnet 2008). Based on several studies, it appears that green roofs provide between 75-90% reduction in heat flow in the summer, but only a 10-30% reduction in the winter, when compared to a typical roof (Dunnet 2008). In either case, the size of the mechanical systems selected can be reduced because of the direct reduction in mechanical load.

One item a design team must assess when implementing a green roof is its size relative to total roof area and vertical surface area. There is a critical roof to wall ratio beyond which the energy savings approach zero. In such cases, these green roofs are relegated to other benefits such as amenity space, storm water management, etc… In "Roof Envelope ratio impact on green roof energy performance," by Martens and Bass (2006), the final conclusion indicated that low, flat, single story buildings had the greatest energy savings over a conventional roof. In 2005, the paper "Energy performance of green roofs in a multi-storey residential building in Madrid," by Alcazar and Bass, indicated that for an eight story building, only the upper three stories showed energy savings due to the installation of a green roof (25% in summer and 12% in winter). Of course, this data is based on a specific building structure. It is apparent, though, that a green roof on a high rise will not have as great an impact as one installed on a low-rise structure. If the energy performance of a building structure is to be assessed, it is recommended that the green roof be modeled.

Green roofs are not the only option for reducing energy usage and providing temperature control. Green walls can provide substantial reduction in daily temperature fluctuations. Studies appear to indicate as much as a 50% reduction (Dunnet 2008). Green walls can simultaneously cool walls, provide window shading, and use evapotranspiration to pre-cool air entering and surrounding the structure. Use of evergreens in green walls can provide winter insulation, while deciduous green walls can allow solar heat gain during winter months.

One potential application of a green wall is as an air biofiltration or precooling system. In the biofiltration system, plants are placed in a biofilter media. The plants are selected based on their ability to assist in the biofiltration process. Using a fan system, installed on the backside of the wall, indoor air contaminants are removed by drawing air through the biofilter. As the air passes through the moist biofilter, it is also cooled. This "pre-cooled" air can be distributed through the building's HVAC system as part of an energy conservation and temperature regulation strategy (Margolis 2007).

Green Roofs, Walls, and Sustainable Metrics

Several United States based sustainability metrics are currently available. Two of these metric systems currently allocate a credit (point) for the use of green roofs. Each credit's intent is to address a specific environmental or social issue. Each metric has its own method of addressing and weighting the importance of these issues. Every engineer should think beyond the point system that these metrics typically use, in order to pursue a truly integrated and sustainable design project. For specific requirements and strategies, please consult the latest guidelines.

USGBC LEED® NC Version 2.2: LEED NC V2.2, "New Construction & Major Renovation" is one of the most popular green building rating systems available through USGBC. A few other notable USGBC rating systems include LEED for Schools, LEED for Healthcare, LEED for Homes, and LEED for Multiple Buildings/Campuses. Although adapted from LEED NC, these rating systems are customized to the end-user. Each rating system uses a credit based certification system to attain certain levels of achievement.

Green Roofs & Walls qualify for several of the following LEED NC credits:

a) Sustainable Site Credit
    a. Green Walls & Façade Greening: Credit 7.1 - "Heat Island Effect Non-Roof"
    b. Green Roofs: Credit 7.2 – "Heat Island Effect Roof",
b) Water Efficiency Credit 1.1 – Reduce potable water consumption by 50%,
c) Water Efficiency Credit 1.2 – Eliminate the use of potable water and surface/sub-surface water resources
d) Water Efficiency Credit 2 – Use Innovative Waste water technologies to reduce wastewater generation (i.e. rainwater capture, recycling grey water)
e) Energy and Atmosphere Credit 1 – Achieve increased levels of energy performance. (See discussion above on energy).
f) Innovation in Design Credit 1 through 4 – Going beyond the LEED NC Green Building Rating System.

Green Globes™: The Green Globes "Design for New Buildings and Retrofits" rating system is an online questionnaire based system that provides early feedback and recommendations through the design process. This system is aimed at commercial buildings. Green Roofs can contribute to several points towards a Green Globe Rating. The assessment areas that green roofs can potentially contribute to are listed below. These assessment areas are similar to the USGBC LEED NC Credit areas.

a) Site B.2 – "Eco Impact – Reduced Heat Island Effect"
b) Site B.3 –"Water Shed Features"
c) Energy C.1 – Energy Performance
d) Energy C.2 – Reduced Energy Demand
e) Water D.1 – Water Performance
f) Water D.2 – Water Conserving Features
g) Water D.3 – On-Site Treatment of Water

Green Roof and Wall Case Studies

Several resources are available for review of case study projects. Probably the best resource available is the 2005

Earth Pledge text titled “Green Roofs – Ecological Design and Construction.” This invaluable text covers over 40 worldwide projects. Each case study includes the green roof size, assembly details, plant selection, soil depth, cost, and weight information. Nigel Dunnett’s, “Planting Green Roofs and Living Walls,” is interspersed with case studies of green roofs and walls. The “Design Guidelines for green roofs,” produced by the Ontario Association of Architects, is also a useful document to consult when determining standard costs for green roof implementation. Manufacturers should also be consulted when specific case studies are sought.

Areas Requiring Further Research & Next Steps

Based on the research performed for this paper it is clear that additional research on the following topics is warranted:

1) Dynamic behavior of green roofs under seismic loads. This may require shake table testing.
2) Anchorage design and detailing of green roofs for seismic loads: flat & sloped roofs. This may require shake table testing.
3) Additional literature review of wind loading on trees and a clear method for calculating base reactions on the structural system. I.e. understanding wind loads and root structure distribution (structural root plate size) for unconfined trees.
4) Additional research related to load determination of green walls. This research should include weight estimations of the plantings and other environmental loads (snow, wind, rain) imposed on the green wall support structure and/or building structure.
5) Additional review of green roof structural failures.

The research behind the structural engineering of green roofs and walls is not yet complete. This paper was merely an attempt to collect information, based on extensive literature review, relevant to structural engineers. Additional research, testing, literature review, and interdisciplinary cooperation will be performed in order to address and quantify these issues.

Conclusion

This document has provided an in-depth discussion on the structural implications of intensive green roofs/terraces, extensive green roofs, and green walls. Design data, resources, and structural engineering strategies have also been provided. It is hoped that this document will provide a resource for engineers looking to easily, safely, and effectively facilitate the integration of green roofs, terraces, and walls into their sustainable design projects.

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Appendix A: Design Load Reference Material

Table A-1: Weights of Common Building Materials

Ref. Dines 1997

Material	**lbs/ft^3 (kg/m^3)**
Granite & Marble	170 (2757)
Slate	160(2595)-180(2919)
Limestone	155 (2514)
Sandstone	145 (2352)
Shale	162 (2627)
Expanded Shale	40 (649) - 45 (730)
Grass-Cel	6 (96)
Fieldstone	95 (1541)
Gravel	120 (1946)
Pebbles	120 (1946)
Pumice	40 (649)
Sand, dry	90 (1460) - 110 (1622)
Sand, wet	110 (1784) - 130 (2180)
Sand and Gravel, mixed	115 (1865)
Clay soil	
compacted, dry	75 (1216) - 100 (1622)
compacted, wet	125 (2027)
Loam, dry	80 (1298)
Loam, wet	120 (1946)
Special commercial soil, wet	110 (1784)
Topsoil, dry	80 (1298)
Topsoil, wet	120 (1946)
Peat, dry	9.6 (154.3)

Peat, wet	10.3 (165.5)
Humus, dry	35 (568)
Humus, wet	82 (1330)

Table A-2: Planting Media Weight
Ref. Dines 1997

Material	lbs/ft^3 (kg/m^3)
Fine Sand, dry	90 (1447)
Fine Sand, damp	120 (1929)
Cedar Shavings, dry	9.25 (149)
Cedar Shavings, damp	13 (209)
Peat moss, dry	9.6 (155)
Peat moss, damp	10.3 (166)
Red Lava, 5/16 in max, dry	50 (804)
Red Lava, 5/16 in max, damp	54 (863)
Redwood Compost and shaving, dry	14.8 (238)
Redwood Compost and shaving, damp	22.2 (357)
Fir and pine bark humus, dry	22.2 (357)
Fir and pine bark humus, damp	33.3 (535)
Perlite, dry	6.5 (105)
Perlite, wet	32.4 (521)
Vermiculite, coarse, dry	6.25 (100.5)
Vermiculite, medium, dry	5.75 (93)
Vermiculite, fine, dry	7.5 (121)
Topsoil, dry	76 (1221)
Topsoil, damp	78 (1254)

Table A-3: Design Vegetation Surface Load
Ref. FM Global 35-1 2007 & FLL Guideline 2002
Note: This table represents minimum design loads. Consult green roof supplier or installer to verify vegetation weight.

Form of Vegetation	lbs/ft^2 (kg/m^2)
Extensive Roofs	
Moss - Sedum	2 (10)
Sedum - moss - herbaceous plants	2 (10)
Sedum - grass - herbaceous plants	2 (10)
Grass - herbaceous plants (dry lawn)	2 (10)
Simple Intensive Roofs	
Grass, rough grassed area	3 (15)
Wild Bushes, coppices	2 (10)
Coppices - shrubs	3 (15)
Coppices (up to 150 cm tall)	4 (20)
Simple Intensive Roofs	
Lawn	1 (5)
Low Bushes and Coppices	2 (10)
Shrubs and Bushes up to 150 cm tall	4 (20)
Bushes up to 10 ft (3 m) tall	6.1 (30)
Large Bushes up to 20 ft (6 m) tall	8.1 (40)
Small Trees up to 33 ft (10 m) tall	12.2 (60)
Trees up to 49 ft (15 m) tall	30.5 (150)

Table A-4: Weights of Containers and Field Grown Plants
Ref. Dines 1997
Notes: 1. Table lists shipping weights, including the box, 2. Cross Reference with "Container Class Table" of ANSI Z60.1-2004, 3. Increase in weight due to growth should be estimated as part of the design process. I.e. This table represents only shipping weights, 4. Container grown weights are based on mushroom compost. Nurseries should be consulted if different compost is used in your region.

Container Size	Container Grown/Field Grown Weights - lbs (kg)
15-gal can (56 L)	80 (36) / --
20 in (510 mm) box	200 (90) / 400 (180)
24 in (610 mm) box	400 (180) / 725 (325)
30 in (760 mm) box	800 (360) / 1500 (675)
36 in (900 mm) box	1300 (585) / 2500 (1125)
48 in (1220 mm) box	3500 (1575) / 6000 (2700)
54 in (1370 mm) box	4000 (1800) / 7000 (3150)
60 in (1520 mm) box	5000 (2250) / 8000 (3600)
72 in (1830 mm) box	7k (3150) / 12k (5400)
84 in (2130 mm) box	9k (4050) / 16k (7200)
96 in (2440 mm) box	12k (5400) / 20k (9000)
120 in (3050 mm) box	14k (6300) / 24 k (10800)

Table A-5: Tree Weight (Green) Algorithms
Ref. Clark 1990
Note: This table includes only a few species. Consult the appropriate forestry and nursery guides for weight algorithms for other tree species. D = Diameter at Breast Height (inches) H = Height of Tree (feet)

Tree species	Size	Algorithm (weight in lbs)
Southern Pine Coastal plane	< 5 inches	$0.32214(D^2H)^{0.91330}$
	$\geq$ 5 inches	$0.19821\,(D^2)^{1.06419}\,(H)^{0.91330}$
Southern Pine Piedmont	< 5 inches	$0.28557\,(D^2H)^{0.92236}$

	≥ 5 inches	$0.18703 (D^2)^{1.05385}(H)^{0.92236}$
Hard Hardwoods	< 11 inches	$0.38315 (D^2H)^{0.92045}$
	≥ 11 inches	$0.11710 (D^2)^{1.16763}(H)^{0.92045}$
Soft Hardwoods	< 11 inches	$0.26153(D^2)^{1.12422}(H)^{0.93871}$
	≥ 11 inches	$0.10743(D^2)^{1.12422}(H)^{0.93871}$
Sweet gum	< 11 inches	$0.24512(D^2H)^{0.95220}$
	≥ 11 inches	$0.09605(D^2)^{1.14754}(H)^{0.95220}$
Yellow Poplar	< 11 inches	$0.16258(D^2H)^{0.99008}$
	≥ 11 inches	$0.12701(D^2)^{1.04157}(H)^{0.99008}$

Appendix B: Sample Structural General Notes for Green Roofs and Walls

GREEN ROOF AND TERRACE ASSEMBLIES

1. LANDSCAPED AND HARDSCAPED AREAS, SUCH AS GREEN ROOF AND TERRACES, SHALL ONLY BE INSTALLED IN AREAS APPROVED BY THE SEOR.
2. MAINTENANCE OF THE GREEN ROOF/TERRACE COMPONENTS AND PLANT GROWTH CONTROL, TO PREVENT STRUCTURAL OVERLOAD AND SERVICEABILITY ISSUES, IS THE RESPONSIBILITY OF THE OWNER.
3. SEE STRUCTURAL LOADING MAPS FOR LOCATIONS AND LIMITS OF PERMANENT SUPERIMPOSED DEAD AND LIVE LOADS, INCLUDING TRANSIENT LOADS, IMPOSED BY GREEN ROOFS AND TERRACES. SECTIONS INDICATED ON LOAD MAPS SHOW INTENT OF DESIGN. COORDINATE WITH LANDSCAPE ARCHITECT AND GREEN ROOF ASSEMBLY MANUFACTURER/SUPPLIER THAT LANDSCAPED AND HARDSCAPED DESIGNS ARE WITHIN THE STRUCTURAL LOAD LIMITS PROVIDED.
4. PROVIDE SUBMITTALS OF THE FOLLOW ITEMS:
   4A. WEIGHTS AND THICKNESSES OF ALL COMPONENTS AND LAYERS. SELECTED ENGINEERED FILL SHALL INCLUDE SATURATED AND UNSATURATED DENSITY AS WELL AS PERMEABILITY DATA.
   4B. DETAIL SECTIONS OF SELECTED GREEN ROOF AND TERRACE ASSEMBLIES.
   4C. DETAILS, LOCATIONS, AND CALCULATIONS OF THE GREEN ROOF/TERRACE ANCHORAGE AND RESTRAINT FOR STATIC AND SEISMIC LATERAL LOADING FOR STRUCTURAL IMPACT REVIEW.
   4D. DRAINAGE PLAN AND STORAGE TANK CUT SHEETS (IF APPLICABLE).
   4E. PROVIDE TREE DATA THAT INCLUDES TREE WEIGHTS, SPECIES, AND BOX SIZES USED ON THE GREEN ROOF. CONTACT INFORMATION FOR THE NURSERY SUPPLIER SHALL ALSO BE PROVIDED. TREE DATA SHALL BE PROVIDED TO GREEN ROOF ASSEMBLY MANUFACTURER FOR LOAD BEARING VERIFICATION OF GREEN ROOF COMPONENTS.
   4F. PROVIDE TREE ROOT BARRIER ASSEMBLIES FOR REVIEW.
5. FABRICATE AND TEST A MOCKUP OF THE FINAL GREEN ROOF ASSEMBLY FOR REVIEW AND APPROVAL. MOCKUP AND MATERIALS SHALL BE TESTED IN ACCORDANCE WITH ASTM E2397 AND ASTM E2399. LOAD AND VOLUME FLOW DATA SHALL BE PROVIDED FOR REVIEW.
6. SEE CSI DIVISION 7 SPECIFICATIONS FOR ADDITIONAL INFORMATION AND REQUIRMENTS.

GREEN WALL ASSEMBLIES

1. GREEN WALLS SHALL ONLY BE INSTALLED IN AREAS APPROVED BY THE SEOR.
2. MAINTENANCE OF THE GREEN ROOF/TERRACE COMPONENTS AND PLANT GROWTH CONTROL, TO PREVENT STRUCTURAL OVERLOAD AND SERVICEABILITY ISSUES, IS THE RESPONSIBILITY OF THE OWNER.
3. SEE STRUCTURAL LOADING MAPS FOR LOCATIONS AND LIMITS OF PERMANENT SUPERIMPOSED DEAD AND LIVE LOADS, INCLUDING TRANSIENT LOADS, IMPOSED BY GREEN WALLS. SECTIONS INDICATED ON LOAD MAPS SHOW INTENT OF DESIGN. COORDINATE WITH LANDSCAPE ARCHITECT AND GREEN WALL ASSEMBLY MANUFACTURER/SUPPLIER THAT LANDSCAPED AND HARDSCAPED DESIGNS ARE WITHIN THE STRUCTURAL LOAD LIMITS PROVIDED.
4. PROVIDE SUBMITTALS OF THE FOLLOW ITEMS:
   4A. WEIGHTS AND THICKNESSES OF GREEN WALL MODULES
   4B. SECTIONS OF SELECTED GREEN WALL ASSEMBLIES
   4C. DETAILS, LOCATIONS, AND CALCULATIONS OF THE GREEN WALL SUPPORT STRUCTURE, INCLUDING ANCHORAGE AND RESTRAINT FOR STATIC AND SEISMIC LATERAL LOADING FOR STRUCTURAL IMPACT REVIEW.
5. FABRICATE AND TEST A MOCKUP OF THE FINAL GREEN WALL ASSEMBLY FOR REVIEW AND APPROVAL. LOAD AND VOLUME FLOW DATA SHALL BE PROVIDED FOR REVIEW.
6. SEE CSI DIVISION 7 SPECIFICATIONS FOR ADDITIONAL INFORMATION AND REQUIRMENTS.